Economic Assessment of Farm Level Climate Change Adaptation Options: Analytical Approach and Empirical Study for the Coastal Area of Bangladesh

DISSERTATION

zur Erlangung des akademischen Grades

doctor rerum agriculturarum (Dr. rer. agr.)

eingereicht an der
Lebenswissenschaftlichen Fakultät
der Humboldt-Universität zu Berlin

von
M.Sc. Fakir Azmal Huda

Präsident der Humboldt-Universität zu Berlin
Prof. Dr. Jan-Hendrik Olbertz

Dekan der Lebenswissenschaftlichen Fakultät
Prof. Dr. Richard Lucius

Gutachter

1. Prof. Dr. Dr. h. c. Dieter Kirschke
2. Priv. Doz. Dr. Christian Franke
3. Prof. Dr. Silke Hüttel

Tag der mündlichen Prüfung: 14. Januar 2015

Economic Assessment of Farm Level Climate Change Adaptation Options: Analytical Approach and Empirical Study for the Coastal Area of Bangladesh

DISSERTATION

Fakir Azmal Huda

Acknowledgements

First, I want to express my praise to almighty Allah (Alhamdulillah), who is merciful and kind, give soul, resources, physical ability, and the knowledge to conduct this study.

I very gratefully acknowledge Professor Dr. Dr. h.c. Dieter Kirschke, Fachgebiet Agrarpolitik, Department für Agrarökonomie, Albrecht Daniel Thaer-Institut für Agrar- und Gartenbau-wissenschaften, Lebenswissenschaftliche Fakultät, Humboldt-Universität zu Berlin, Germany, for his scholastic guidance, constructive comments, and valuable suggestions as a promoter of the research work.

I am also indebted to my teacher of econometrics, PD Dr Christian Franke, for his cordial co-operation in conceptualizing the econometric models. His supportive suggestions and intellectual perception helped me carry out the study.

I am grateful to Mr Yousef Jameel for the finance and study support, through the Yousef Jameel Scholarship. The fellowship created a good basis for my life in Europe and my PhD research.

My sincere gratitude and cordial thanks are extended to Mrs Helga Meaini and Mrs Kerstin Oertel for their time, support, and logistic help in conducting the research, as well as encouragement to complete the study.

Appreciation and cordial thanks are also extended to Mr Atiqur Raman, Mr Gazi Mostofa Kabir Uddin, and Mr Md. Abul Fajal who volunteered for conducting the survey in Bangladesh. I also gratefully acknowledge the supportive help from Mr Md. Shohel Aaban Rana as his expertise on computer composition and other computer related knowledge was applied to this work.

Endless love and affection to my wife, Shawkat Ara Popy, daughter, Maliha Zareen Tasnim, and son, Fakir Abdullah Ahmed Araf, for their sacrifice, compromise and inspiration in the time of my research work and study period in Europe.

Table of contents

List of tables

List of figures

List of abbreviations

AEZ	=	Agro-ecological Zone
AR4	=	Assessment Report 4
BARC	=	Bangladesh Agricultural Research Council
BBS	=	Bangladesh Bureau of Statistics
BDT	=	Bangladeshi taka
BLS	=	Bacterial Leaf Steak
BMDC	=	Bangladesh Meteorological Development Corporation
BRRI	=	Bangladesh Rice Research Institute
CEGIS	=	Center for Environmental and Geographic Information Services
CH_4	=	Methane
DAE	=	Department of Agricultural Extension
DSSAT	=	Decision Support System for Agro Technology Transfer
FAO	=	Food and Agricultural Organization
FGLS	=	Feasible Generalized Least Square
GDP	=	Gross domestic product
GHG	=	Greenhouse gas
GLS	=	Generalized Least Square
GOB	=	Government of Bangladesh
IFDC	=	International Fertilizer Development Centre
IPCC	=	Inter-governmental Panel of Climate Change
MOFE	=	Ministry of Forest and Environment
NGO	=	Non-government organization
SAARC	=	South Asian Association for Regional Co-operation
SMRC	=	SAARC Metrological Research Centre
SRES	=	Special Report on Emissions Scenarios
UNDP	=	United Nations Development Program
WB	=	World Bank

Summary

The adaptation of farming to climate change is gaining importance in policy and scientific debates as almost all farm activities and production depend on weather and, therefore, are climate sensitive. Recently, the adverse impacts of climate variability and change on traditional farming are visible in developing countries. This bio-physical change in the production environment has directed farmers towards strategic alternatives for farming practices. The economic assessment of these adaptation options is of great importance in facing the uncertainty of climate change. However, the economic assessment of farm level adaptation options remains in its infancy with few empirical studies. Cross-sectional and time series observations are necessary for having details on the impacts.

The present thesis aims at developing an integrated economic framework for the assessment of adaptation options, using farm level panel data of rice farming in the coastal area of Bangladesh. Bangladesh is one of the most vulnerable countries to the effects of climate change, and the coastal area is a good example of climate-prone farming. The study is also a pathway for further empirical studies on the impacts of climate change on agriculture. The study framework analyzes economic implications of alternative farming activities relating to climate change in several dimensions. The theoretical and empirical economic approach of the study can be characterized in two distinct ways: the process-based approach following farm management theory by production performance analysis and the appraisal of adaptation; and the hedonic (Ricardian) approach based on land rent theory and the change in net farm income in relation to climatic variables, as well as parametric estimation of an econometric model.

The analysis of input-output relations of rice farming was done based on an intensive survey of 300 adapted farmers over 8 years at different climate thresholds. The study assesses different adaptation options for two rice growing seasons, namely *Boro* and *Amon*. It finds that farm income is significantly susceptible to damage from climate variability. The descriptive analysis depicts the current status of climate shocks, alternative production options, and risks of rice production. Fourteen adaptation options were found in the area for the two growing seasons. A combination of several farming practices, such as crop management, fertilizer application efficiency, and irrigation and rainwater harvesting, achieves three kinds of benefits. These are low resource use, moderate productive performance and high farm net income; reduced GHG production; and farms coping with changing climatic

conditions. The study reveals that marginal impacts of temperature on farm net income are negative for all seasons. The marginal impacts of rainfall were found to be positive and significant for all models in the study. It is also evident from the analysis that successive adaptation significantly increases farm productivity and contributes to the revival of farm revenue up to a threshold level. Finally, based on estimated climate variability models of farm net income, the study presents a model that simulates according to future climate change scenarios. It indicates adverse effects of climate change on future farm income. As climate change is a continuous process that relates to global economic development, alternative production systems under adaptation strategies should be continually reshaped by innovative research, favorable policies and extension.

Key words: Climate change, adaptation, hedonic approach and farm net income.

Zusammenfassung

Die Anpassung der Landwirtschaft an die Klimaveränderung hat in der Politik und in wissenschaftlichen Debatten enorm an Wichtigkeit gewonnen. Ein Großteil der landwirtschaftlichen Produktion ist klimasensibel, von natürlichen Wetterbedingungen abhängig, und der nachteilige Einfluss von Klimavariabilität und -wandel zeigt sich bereits in Entwicklungsländern. Die biophysikalischen Veränderungen der Produktionsbedingungen veranlasst Landwirte zu strategischen Änderungen ihrer herkömmlichen Produktionsprozesse. Um den Unsicherheiten zukünftiger Klimaentwicklungen zu begegnen, ist die ökonomische Bewertung dieser Anpassungsmaßnahmen und -optionen von großer Bedeutung. Die ökonomische Bewertung von betrieblichen Anpassungsoptionen befindet sich jedoch noch im Anfangsstadium, und es liegen nur wenige empirische Studien vor. Querschnittsstudien und Langzeitbeobachtungen sind notwendig, um detaillierte Erkenntnisse ableiten zu können.

Vor diesem Hintergrund zielt die vorliegende Studie auf die Entwicklung eines integrierten ökonomischen Rahmens für die Bewertung von Anpassungsoptionen ab, beruhend auf der Nutzung von Panel-Daten des Reisanbaus im Küstengebiet von Bangladesch. Bangladesch ist eines der am stärksten vom Klimawandel gefährdeten Länder und ein gutes Beispiel für eine besonders klimaanfällige Landwirtschaft. Die vorliegende Studie zeigt einen Weg für weitere empirische Studien über die Auswirkungen des Klimawandels auf die Landwirtschaft. Das in dieser Studie entwickelte Vorgehen ermöglicht die Analyse ökonomischer Auswirkungen alternativer Anpassungsmaßnahmen in mehrerer Hinsicht. Der theoretische und ökonometrische Ansatz lässt sich hinsichtlich zwei Charakteristika beschreiben: (1) ein prozessorientierter Ansatz aufbauend auf der Theorie des Betriebsmanagements unter Verwendung einer Analyse von Produktionsleistungen und Anpassungsoptionen und (2) ein hedonischer bzw. Ricardianischen Ansatz basierend auf landrententheoretischen Ansätzen und Veränderungen des Nettobetriebseinkommens in Relation zu klimatischen Variablen sowie parametrischen Schätzungen eines ökonometrischen Modells.

Die Analyse von Input-Output Verhältnissen der Reisproduktion basiert auf einer umfassenden Befragung von 300 „klimaangepassten“ Landwirten über acht Jahre. Im Rahmen der Studie werden verschiedene Anpassungsoptionen für zwei Wachstums- bzw. Anbausaisons von Reis bewertet: *Boro* und *Amon*. Im Ergebnis zeigt sich, dass die Betriebseinkommen sehr anfällig für klimainduzierte Schäden sind. Die deskriptive Analyse verdeutlicht den gegenwärtigen Status von Klimaschocks und alternativen Anbauoptionen und -risiken des

Reisanbaus. In der Untersuchungsregion wurden 14 Anbauoptionen für die zwei Anbausaisons identifiziert. Eine Kombination von verschiedenen Produktionsmethoden wie Anbaumanagement, effiziente Düngung oder Regenwassernutzung ermöglicht die Realisierung von drei verschiedenen Vorteilen. Hierbei handelt es sich um (1) eine geringere Nutzung von Ressourcen in Kombination mit einer moderaten produktiven Leistung und einem hohen Nettoeinkommen, (2) eine Verringerung von Treibhausgasemissionen, und (3) einen klimaangepassten Betrieb. Die vorliegende Arbeit zeigt auch, dass die Effekte marginaler Temperaturänderungen auf das Betriebseinkommen negativ für die *Amon* Saison und für die *Boro* Saison sind. Die marginalen Auswirkungen von Niederschlag sind in allen Modellen signifikant und positiv. Aus der Analyse geht eindeutig hervor, dass eine sukzessive Anpassung die Betriebsproduktivität signifikant erhöhen kann und bis zu einem Grenzwert die Betriebseinkommen ankurbelt.

Basierend auf den geschätzten Klimamodellen werden in der Studie zukünftige Klimawandelszenarien simuliert und deren Auswirkungen auf das Nettobetriebseinkommen modelliert. Es werden die nachteiligen Effekte des Klimawandels auf zukünftige Betriebseinkünfte aufgezeigt. Klimawandel ist ein kontinuierlicher, in engem Zusammenhang mit der globalen wirtschaftlichen Entwicklung stehender Prozess. Demzufolge sollten alternative, auf neuen Anpassungsstrategien beruhende Produktionssysteme kontinuierlich mittels innovativer Forschung untersucht werden, und es bedarf unterstützender Klimapolitiken sowie einer Ausrichtung auf Beratungsdienstleistungen.

Schlagwörter: Klimaveränderung, Anpassung, hedonischer Ansatz und Betriebseinkommen.

1 Introduction

1.1 Problem statement

Climate change is a global problem generated from the human activities that have come from industrialization and civilization. Scientific evidence is clear about Greenhouse gas (GHG) effect created from industrial emission (IPCC 2005). In understanding climate change and global warming, it is important to examine all economic activities and how they contribute to the problem. The agricultural sector is one of the most vulnerable to the effect of climate change. In light of the Third Assessment Report of global climate change prediction by IPCC, there is concern about the consequences of climate change on the agricultural sector. Local farm communities in parts of the developing world have already experienced food security and traditional livelihood problems due to climate variability (FAO 2006, IPCC 2007a). These are mostly coastal areas and small islands which have seen drastic changes in agro-climate conditions and the environment for agriculture. Crop farming is vulnerable to weather or climate variability shocks; frequent sea storms and associated flooding cause salinity intrusion in crop fields, an increase in the days of high temperature, erratic or less frequent rain and seasonal drought all pose a threat to existing farming systems. The yield and farm income, especially in coastal agriculture, has decreased from a threshold level. In this context, the negative impact of climate change is predicted to be an increase in days of high temperatures, variable rainfall, and extreme climate events such as floods, cyclones, droughts and rising sea level (Sarker 2012, Isik and Devadoss 2006, Molua 2009, IPCC 2007b). Agricultural vulnerability to climate change will lead to local livelihood and food security problems in a new dimension. Consequently, climate change is an additional challenge for operating risky farm business profitably. A crop yield may be smaller if it is grown in the same place under climate shocks. If no adequate mitigation strategies to control GHG emissions are implemented, the subsequent effects of climate change will hurt local traditional farming in developing countries unless the farmers adopt alternative management practices. In the face of extreme climatic variations, adaptation may be an efficient resilience options (Adger et al. 2003)**.** However, alternative farm management in the context of climate change also depends on the adaptive capacity of the farmer and the public and private investment. The overall remedy for the problem of climate change and farm-level adaptation dynamics is very complex.

Geographically, Bangladesh is situated in a low lying delta, prone to the effect of climate change (BBS 2008). In fact, Bangladesh is ranked number five in world vulnerability index (Kreft and Eckstein 2014). The country's coast is one of the longest in the world (5107 km), and the area is ecologically sensitive and climatically vulnerable. There are about 6.8 million of rural farm households within 147 *Upazila* (sub district) in this coastal zone living off of agriculture and fishing (BBS 2004). With agricultural production and fish availability, the zone already suffers from continued global warming effects (Rashid and Islam 2007). In addition to this the weather drastically reduces milk yields and fish production. Crops like rice, wheat, pulses and rape seeds are also susceptible to infestation of pests and diseases in weather under the effects of climate change (Rashid and Islam 2007).

Temperature data in Bangladesh has shown rising trends, particularly in summer and the monsoon season over the last three decades (UNDP 2007, GOB 2005). The estimated average temperature has risen by 0.7°C per decade across Bangladesh (Ahsan et al. 2011). Moreover, it is expected that in the year 2030 the country's temperature will have increase 1^0C. In the year 2050, it is expected that the increase will be 1.4°C (FAO 2006, IPCC 2007). Consequential impacts such as water stagnation, salinity intrusion, and seasonal drought with high humidity already severely hamper agricultural production and cropping intensity. The average rise in sea level in the southwestern region is 4mm per year (SMRC 2003). The salinity-affected areas increased by 10 percent from 1973 to 2000 and the salinity level increased from 2ds/m to 15ds/m in some southwestern coastal areas. Erratic rain causes water stagnation, flood and even seasonal drought, and severely hampers the *Amon* season rain-fed rice production (Rashid and Islam 2007).

Rice dominates the crop agriculture in Bangladesh. The rice yield has been decreasing due to the shocks of high evaporation-transportation, salinity in the soil, and temperature brought on by climate change. Consequently, traditional farm income and food security are vulnerable to such shocks. Overall climate shocks will reduce rice yields by 17 percent as predicted by the Bangladeshi government (GOB 2005).

Current climatic variation forces farmers to adopt new methods of agricultural production for rice farming. These adaptation measures are important in helping these communities established efficient resilience in the face of climatic variation and associated extreme weather conditions (Adger et al. 2003). Alternative methods have the potential to significantly reduce negative impacts from changes in climatic conditions (Kandlinkar and Risbey 2003).

In Bangladesh, a number of studies were conducted on the effect of climate change on rice. Most of them are related to crop simulation modeling or scenario-based modeling. However, as these studies are not conducted on farm-based data, they are unable to reveal the economic effects of climate change on farms. Furthermore, these are all descriptive and only focus on sudden weather variability and the relevant impacts. A comprehensive and integrated quantitative analysis of farm income vulnerability to the impacts of climate change and adaptation is necessary. There is a need both for cross-sectional and time series data analysis of the climate on farm income.

While many economists have examined the potential impacts of climate change on farms, surprisingly few attempts have been made to systematically analyze farm level adaptation, and the possibility of a farmer to shift from one agricultural practice to another in response to climatic conditions. Processes that could properly shape farmers´ adaptation is limited in previous studies and rarely understood. How could farm business operate in an optimum manner so as to achieve maximum net revenues despite being vulnerable to be the effects of climate change?

Therefore, an economic assessment of adaptation options to climate change and the relating constraints to adaptation is important for Bangladesh's agricultural community. A better understanding of farm productivity based on both cross sectional and time series analyses of climatic change is necessary. The current adaptation measures and their determinants will be important to inform policy makers about the future successful adaptation of the agricultural sector. The knowledge of adaptation methods might improve policies towards tackling the challenges that climate change is imposing on Bangladeshi farmers. This research will provide economic insights into rice farming regarding changes in climate and adaptation options.

1.2 Research objectives

The main objective of the study is the assessment of the susceptibility of farm income to climate change and the adaptation options at the farm-level in the coastal areas of Bangladesh. The specific objectives are as follows:

1. to conduct a survey to gain insight into the farm-level practices being employed in adapting to the effects of climate change in rice farming in coastal Bangladesh;

2. to assess the economic implications of specific adaptation options on rice farms under climate change; and

3. to assess the impact of climate variability and adaptation options on productivity as well as on farm earnings in future climate change scenarios.

1.3 Scope of the research work

The study is organized in seven chapters. Following the introductory chapter, chapter two presents the state-of-the-art in farm-level climate change impact assessment and economic analysis of adaptation options. The theoretical background of climate change, crop agriculture and economic analysis is reviewed in this chapter. The assessment framework is based on economic instruments which are represented as assessment of the farm net income in response to climate change. In addition to this, to ensure a comprehensive understanding of the issue, relevant empirical studies are discussed.

Chapter three is focused on the methodology employed in the research work and farm survey. It includes the description of the study sites and the methods used in the survey. The sampling procedure and the nature of the data sources are also discussed in this chapter. The overall design of the study, including the different process of research work and relevant instruments of analysis are presented in this chapter.

Chapter four provides insight into the adaptation options at the farm level. The farmers´ perceptions and frequencies of different adaptation options are described in this chapter. All descriptive and tabular attributes of climate shocks and evidences are provided here. The chapter details out the inside story of alternative production practices, adaptation performance, and mitigation potential of negative impact of climate change.

Chapter five analyzes the economic implications of adaptation options in rice farming. The chapter aims to identify the merits of coping mechanisms among the available options using traditional farm management analytical tools and descriptive statistics. It focuses on and provides the details of several farming practices of crop management, fertilizer application efficiency and irrigation and rainwater harvesting. Finally, the chapter points to pathways to low carbon farming under different adaptation practices.

Chapter six comprises the assessment of several dimensions of climate change impacts and adaptation options. Econometric models were used to estimate and assess farm net income for different thresholds of rice farming. The hedonic (Ricardian) approach to climate change impact was used in this chapter. Finally, based on the estimated climate variability models of farm net income, the study uses the models for an IPCC scenario prediction and a climate change forecast which reveals the adverse effects of climate change on future farm revenues.

Finally, chapter seven presents a summary and conclusions. It also discusses some policy options and implications from the results, and future research topics.

2 Climate change and adaptation option assessment at the farm level: the state of the art in economics

Adapting agriculture and farming system to climate change is a vital policy concern for the agricultural sector. This chapter introduces the economic framework for analyzing farm-level climate change impacts and adaptation options. Reviewing contemporary impact and adaptation studies, it discusses how the design of research into the impacts of climate changes under uncertainty and adaptation dynamics could be developed. The assessment framework is based on economic instruments which are represented by analysis of farm net income in response to climate change. In so doing, the chapter discusses empirical econometric model formulation for measuring the degrees of response in farm performance in relation to climate parameters and adaptive capacities. Finally, the chapter concludes with some proposals for policy making and further empirical research on climate change.

2.1 Introduction

The basis of farming is natural resources, climate and farm community goals. The first two drivers are combined in eco-system services and the third one determines the optimal production systems from the farmers' points of view. In the development stages, population growth worked as a key driver for expansion in the cultivation of land within the given eco-system services. In the process of expansion, the highly productive land was exploited first followed by, moderately productive land. In the last century, marginally productive land was exploited in demand for food, fiber and to a small extent, bioenergy.

In view of this evaluation, a historical focus in research was given to rising agricultural production, especially technological improvement. Successful innovations increase crop production and promote the use of high-yielding varieties, as well as hybrid varieties with intensive technology.

Besides this, the industrial revolution and contemporary economic growth lead to a global imbalance of atmospheric CO_2-cycle. IPCC claims that at the pre-industrial revolution level, atmospheric CO_2 concentration was only 335 parts per million (PPM), at a time when the total carbon cycle was in balance in terms of origin and oceanic uptake. The expansions of agricultural land by deforestation as well as excessive CO_2 emission from industries have broken the global carbon cycle balance (IPCC 2014, IPCC 2003).

The IPCC predicts that the atmospheric CO_2 concentration of the pre-industrial period will have doubled within the next 50 years (IPCC 2003). It forecasts different scenarios of CO_2 emission probabilities. The presence of excessive CO_2 in the atmosphere will create global warming problems. The average global temperature already is about one degree Celsius higher than in the pre-industrial period (IPCC 2014).

The implications of such changes in climate indicate the melting of ice and the problem of rising sea levels (Climate Institute 2014). Sea flooding in coastal areas by frequent storms adversely affects soil and eco-system services for salinity intrusion. Global warming is also responsible for seasonal drought, precipitation problems, and natural disasters like cyclones and tsunamis. The eco-system service is no longer favorable for agricultural production (World Bank 2009). In several regions, productivity, farm livelihoods, food security and farm income are under threat.

In the context of climate change, the farming system is characterized by adopting new production practices. The uncertain production framework is the variability of temperature, precipitation and salinity intrusion. The changing climate affects the eco-system services which impact on crop yields; consequently, farm income is vulnerable to climate change.

To reduce this vulnerability to climate change, farm management reacts through modifying farming practices. This may be called an integrated approach of adaptation to climate change. There are two basic economic implications at the farm level to be assessed: 1. the impact of climate change without adaptation, and 2. the impact of adaptation options in the framework of uncertainty. Uncertainty is one of the most important research problems found in the study. Hence what is the current state of theory for assessing farm-level adaptation options under climate change?

This chapter introduces an analytical framework for the analysis of the two above-mentioned issues. It aims to link existing bio-physical analytical frameworks to an economic and policy perspective of adaptation options. The framework builds on classical economic theory of land rent by Ricardo (1817) and the structural Ricardian theory developed by Mendelsohn, Nordhaus and Shaw (1994). The chapter reviews the economic literature on the impacts of and adaptation to climate change. Following this, it highlights current state of the relevant theories and empirical studies.

2.2 Interlinks of the climate system, agriculture and the economic framework

The economic framework that intends to downscale and assess the impacts of climate changes on agriculture needs to be correctly specified. The nature of interdependent changes, extreme event due to CO_2 concentration and gradual changes in climate system that hits farm threshold production have to be considered in the framework.

It was effectively introduced by Tubiello and Rosenzweig (2008) that claimed the warming of up to 2°C in the early 21st century may positively affect crop and livestock yields in temperate regions, while it will adversely affect the semi-arid and tropical regions. Further warming due to climate change would likely reduce crop yields in all parts of the world. There is a definite relationship between the climate system for agriculture and the associated farm income (Tubiello and Rosenzweig 2008). For instance, the way to approximate the different framework of relationship with which changes in climate is working in farms is illustrated in the figure 2.1 and described in the following sub-section.

2.2.1 Climate shocks and farm earnings

The vulnerability of yields to climate shocks reduces net farm earnings as compared to a climate threshold level. Other things remaining equal, lower factor endowments will obviously lower farm net income. In cases of unchanged commodity prices, a one percent decline in agricultural productivity will lead to a two percent decline in farm income on average (Hertel, Burke and Lobell 2010). But in cases of massive productivity reduction, commodity prices would certainly rise relative to the threshold level. Such price movements depend on relative price elasticity of the commodities and farm-level demand.

Considering input costs and farm earnings together, subsistence farmers and the marginal farmers will be hurt by climate shocks. The welfare loss will be the higher the more inputs are needed for crop protection under shocks or the farm products used for home-consumption at high price are accredited in welfare measurement.

On the contrary, Adams, et al. (1998) emphasized that farmers' gain from adverse climate shocks could be high but due to inelastic demand for agricultural product the gains will be reduced by lower revenue.

2.2.2 Implications of farm vulnerability

Climate change is very much relevant to vulnerability as it affects the susceptibility to damage on farm. Without climate change that would be a threshold-level of variability. Then, exposure to external disturbing climate forces will have an impact on the susceptibility to damage. Therefore, the assessment of farm vulnerability interlinks with an outcome-based assessment of climate change. The analysis focuses on multiple causes of a single outcome. For agriculture, it will measure the susceptibility of yields or farm income to climate shocks. To characterize farming systems under climate change, the measurement of sensitivity and exposure is a crucial factor. The link of sensitivity and exposure to farm productivity combine exposure and climate change analysis. It expresses the frequency distribution of temperature and sensitivity of yield or more specifically the change in yield, as a result of temperature or precipitation changes.

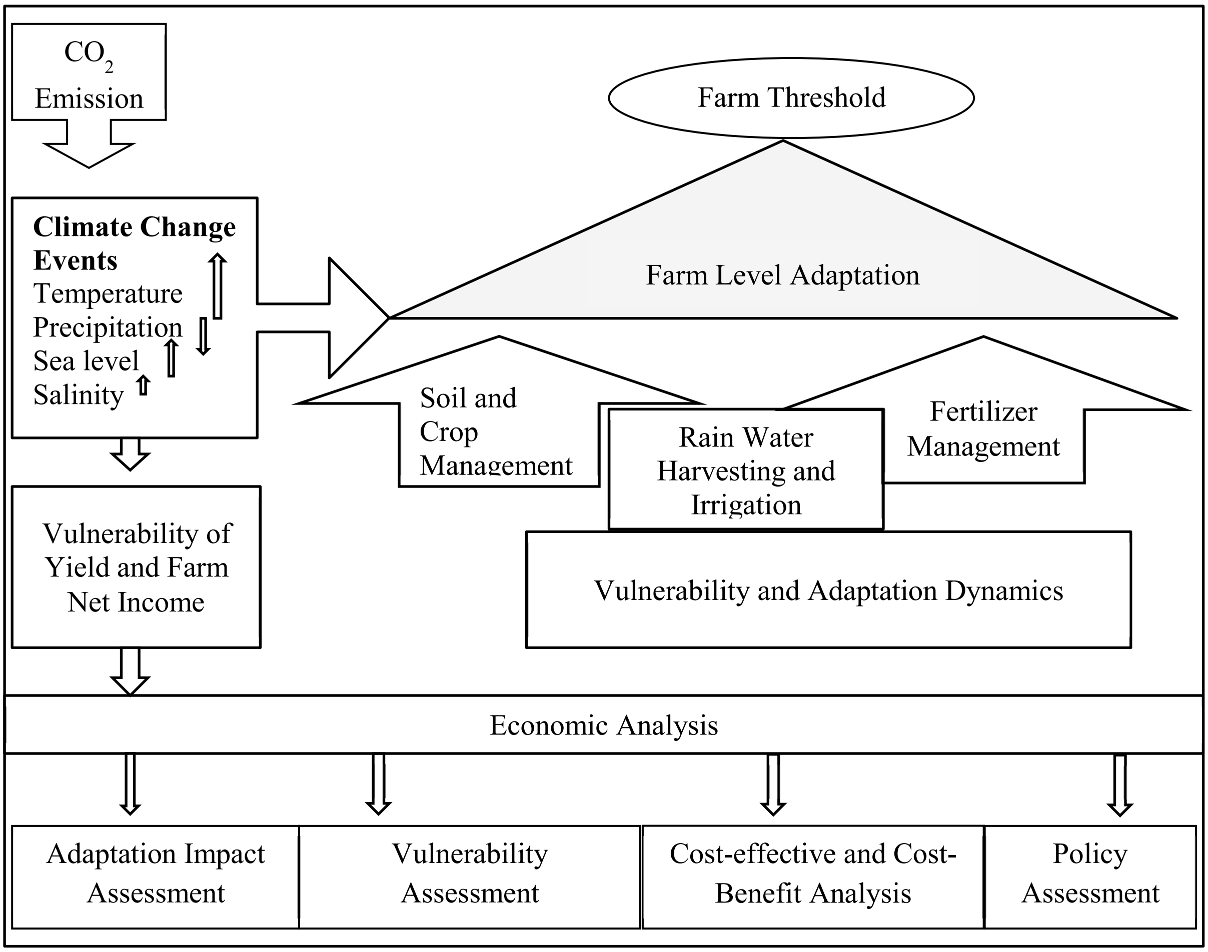
2.2.3 Adaptation options, climate risk and on-farm economic implications

The linkage of a climate system and agricultural production raises the question about available adaptation options. The impact of climate change on farming depends on the time over which it occurs. Farmer would be better off adopting gradual changes. In the short-run they are unable to adjust to changes and are bound to bear the damage of climate shocks. Impacts that require changes in the short-run do not provide sufficient time for adaptation. However, in the case of a gradual and long-term change, the process of farm level adaptation will occur in a diverse way.

Ziervogel et al. (2006) shape the dynamic process of adaptation for agriculture and livestock with respect to environmental and social factors. These are distant from infrastructure facilities, water resources and availability of precipitations. The adaptation decisions are also influenced by social capital, for example a social safety net, trade policies, market price support, land tenure and water rights, and participation with development processes (Adger et al. 2007, Kelly and Adger 2000, Smit et al. 2001, Smit and Wandel 2006).

It is challenging to get empirical observations for these complex factors and forecast potential adaptation to forthcoming climate events. In the study, the focus is on the related frameworks for farm-level adaptation options.

Figure 2.1 Interlink of the climate system, agriculture and the economic framework



Source: Author's own elaboration

Several contemporary surveys of farm-level adaptation, including empirical analyses exist in the climate change literature. Farmers have a choice between a variety of risk-minimizing techniques, such as variety diversification against climate risk, crop management, soil and water management, and fertilizer management illustrated in figure 2.1. Adjustment now will reduce the potential damage of climate change in the long-run. Any adjustment will lead to changes in land use.

Gine et al. (2007) observed Indian farmers in Andhra Pradesh. They are adopting strategies of mixed cropping that reduce the climate risks for farm revenue. The farmers plant a variety of crops to reduce the variability of their income. Despite the practice, farm income is reduced from a threshold level without the effects climate change. Farmers' adaptation strategies for mitigating climate risk depend on economic, environmental and the entrepreneurial decision.

Ziervogel et al. (2006) find that the degree of adaptation in farm households varies with the size of the farm. Wealthier or large farms are typically less diversified and they are targeting market demand and maximizing profit. Rosenzweig and Binswanger (1993) find that high rainfall reduces farm profits for small farms or those in the poorest quartile by 35 per cent. The richest quartile seems to remain virtually unaffected by more uncertain rainfall.

The inter-link of climate system, agriculture and economic framework assists in describing the implication of vulnerability of farm income to climate change and the assessment of impacts resulting from adaptation to climate change. The assessment of the economic implications of adaptation practices helps to understand adaptation as an investment. The key issues are impact assessment, cost effectiveness, and potential benefits and costs of adaptation from an investment perspective. In addition, assessing policy responses may help to understand policy options and priorities at the farm-level.

2.3 Farm-level climate change and adaptation options assessment framework: what is the current state?

In the context of a user's perspective, Hertel and Rosch (2010) categorize the vast literature on the assessment of the agricultural impact of climate change into three groups: crop growth simulation models, statistical studies, and hedonic approaches. The strengths and weaknesses of each approach are discussed by Rowhani and Ramankutty (2009). Relevant issues are the burdensome data requirement and whether the approach has a spatial implication. Further issues are whether the methodology is process-based and what the potential of capturing threshold effects and adaptation responses to climate change is. Finally, whether or not the model can be validated or tested is a key issue. The details of different assessment frameworks are critically discussed in the following sections.

2.3.1 Process-based crop yield simulation approach

According to Nelson et al. (2009), several recent studies used bio-physical crop growth simulation models for impact assessment. A process-based model simulates crop growth as a function of climate parameters such as temperature, precipitation and soil including nitrogen dynamics. In this assessment tool, plant leaf and stem growth rates are calculated in the context of a study of six stages of bio-climate interaction. In addition to this, there are some managerial inputs that can be in the model to simulate the impact of climate change according to temperature and precipitation variation; these inputs, in the most cases are variety choice, planting dates, row spacing, and irrigation and nitrogen application. The approach called the Crop Environmental Resource Synthesis Model was implemented through the Decision Support System for Agro Technology Transfer (DSSAT). The authors estimated climate response yield variations for developing countries for 2050. They found the yield variations ranged from 1 percent for rain-fed rice and wheat, to 19 percent for irrigated rice and 34 percent for irrigated wheat.

The important characteristic of crop models is the simulation of growth in stages so that every event can be assessed, even daily. Extensive data is required for this model and explicit spatial resolution can be considered in the earth surface applications. For any adaptation practice, model users are able to identify varieties, fertilizer application and irrigation availability.

Hertel et al. (2010) argue that despite the highly calibrated nature of field-based approach in global studies, the DSSAT has not been validated globally. This limitation introduces a new idea developed by Deryng et al. (2011) called the Agro-PEGASUS model. It has the characteristics of a less-highly calibrated variant of crop simulation. It simulates growth as a function of light use efficiency, average daily absorbed photo-synthetically active radiation, temperature, soil moisture, and fertilizer availability, and may be applicable in global scale (Deryng et al. 2011).

The prediction for planting and harvesting maize with the Agro-PEGASUS model matches the observed yields. For a 2°C rise in global temperatures, the model finds that average maize and soybean yields may rise in high-income countries while falling slightly for wheat. For countries with lower incomes, it finds the sharpest yield losses: ranging from 13 per cent for spring wheat to 22 per cent for soybean and 27 per cent for maize. The model suggests that due to the enormous reduction in productivity, countries with lower incomes will experience considerable farm income losses (Deryng et al. 2011). Interestingly, Hertel et al. (2010) comment critically on the Agro-PAGASUS model, saying that it is not yet available to a broader research community, but consider it as an instrument for keeping an eye on future research.

2.3.2 Integrated assessment or statistical approach

IPCC first introduced an assessment for understanding the impacts of climate change on the agricultural system for 1990 (IPCC 2003). The assessment is synthesized knowledge of understanding actual changes in the climate and its impacts. The early assessment efforts focused only on impacts, ignoring potential adaptations which may be crucial for climate change management. Recent studies incorporate the possibility of adaptation by using an integrated assessment or statistical approach. They refer to system models that integrate different sub-systems of climate, crop growth, economy and environment and can operate on spatial scales from the farm to a global range (Antle and Capalbo 2010). Integrated assessment modeling studies are linked with crop growth models for simulating the impacts on crop productivity. They then use knowledge of productivity changes in the economic models that would identify economic impacts. Thus, incorporate planting dates and another influence of genetic characteristics of crop varieties in economic models may be applicable. These models typically use farmers' positive decisions to allocate land for crops according to profitability.

An integrated model was used for a US agriculture assessment study by Reilly et al. (2003) and updated by McCarl et al. (2008). It simulates increasing atmospheric CO_2 concentration levels in a crop growth simulation model under rain-fed and irrigated systems (McCarl et al. 2008, Reilly et al. 2003). The model was used for present adaptation practices and expected adaptation scenarios of changing plantation dates, as well as other options of adaptations to a hot climate. Some economists criticized the model because of its limited ability to simulate all adaptation options that could occur in response to climate change (Hertel and Rosch 2010).

Schlenker, Roberts, Lobell and Field offer an alternative approach to overcoming this limitation, called a statistical approach. This statistical modeling approach estimates the statistical relationship between productivity of farms and climate parameters. Although this is not a process-oriented approach, it is useful in predicting future responses based on past relationships. The approach can be based on cross-sectional data together with time series data (Schlenker and Roberts 2006, Lobell and Field 2007, Schlenker and Lobell 2010).

Cross-sectional data analysis focuses on long-run adaptation to climate change. The analysis focus has problems with omitted variables bias (Hertel and Rosch 2010). On the other hand, time series analysis concentrates on the impact of year-to-year changes in climate on yield variation (and economic return). The approach estimates the short-run impact of climate change on yields where climate change is not fully anticipated. The time series approach was used to examine the US crop yield variability in view of climate conditions. It found lower crop yields and higher yield variability due to the changing climate. However, the time series approach, with respect to yields and climate change limited in length, has large standard errors. And there is uncertainty about the forthcoming impacts of temperature and precipitation McCarl et al. (2008).

Schlenker and Roberts (2006) advise using panel data to overcome the problem where a cross- section of yields is followed over time, and using fixed-effect analysis to account for regional determinants of yields. Their study on maize response to temperature in the north of the US identifies a clear threshold of 30^0C; beyond this, subsequent increments in temperature drastically reduce yields. The pattern of yield response to temperature is non-linear form according to empirical model they used.

The advantage of panel data or the statistical approach for analyzing the impact of climate change on farming depends on its methodological nature. The data requirement is relatively small, it has a spatial resolution, and the goodness of fit is higher. The model can be tested for validity using historical changes and prediction used out of sample. The big limitation of the model is the focus on the yield response without considering adaptation dynamics. However, the model is an effective approach for adaptation analysis beyond climate impact analysis.

2.3.3 Hedonic (Ricardian) approach

(a) Ricardian (cross-sectional) approach

Mendelsohn et al. propose a new approach for overcoming the limitation of adaptation dynamics, called the hedonic approach (Mendelsohn, Nordhaus and Shaw 1994). The approach is also popularly known as Ricardian approach. They assumed farmers are changing their mix of activities in favors of crops that yields the highest returns from a unit of land. The approach identifies valuation factors following the assumption that the value of any natural resource service is determined by its internal characteristics. The valuation of land productivity using the eco-system service idea is first discussed in economic theory as the Ricardian theory of land rent dates back to 1817.

The approach focuses on the impact of climate change on land values, not yields. The basic idea is similar to the statistical approach. It then uses historical data to estimate the statistical relationship between economic values of land or farm earnings and climate variables. This statistical relationship may represent all the actual adaptations in the reduced form statistical model. The approach can be used to estimate the long-run economic value of climate change as well as the impact of adaptation under a new climate system.

The hedonic approach depends on two basic assumptions. The first one is a long-run equilibrium in land markets. The second assumption is that there are no adjustment costs such as land rents that fully reflect the value of the climate at any given location. Under these basic assumptions farmers wish to maximize farm income subject to the exogenous conditions of the farm. More accurately, the farmer chooses the crop mix and inputs that maximize net farm profit for each unit of land represented in the following equation.

$$max\, \pi = \sum_i P_{qi}\, Q_i\big(X_{i,}L_{i,}IR_{i,}C_,W_,S\big) - \sum_i P_x\, X_i - \sum_i P_L\, L_i - \sum_i P_k\, K_i - IR_i \qquad (2.1)$$

where π is net annual income, P_{qi} is the market price of output i, $Q_i(X_{i,}L_{i,}IR_{i,}C_,W_,S)$ is the production function for crop i, X_i is a vector of the annual inputs for each crop i, L_i is vector of the labor for each crop i, K_i is a vector of the capital cost for crop i, C is a vector of climate variables, IR_i is a vector of the irrigation choice for each crop i, W is the available water for irrigation, S is a vector of the soil characteristics, P_x a vector of the prices for annual inputs, P_L is a vector of the prices for labor, P_k is the rental prices of capital, and P_{ir} is the annual cost of each type of irrigation system.

The farmer would choose the crop that provides the highest possible net income and endogenous input in order to maximize net income. The farm net income will be a function of just the exogenous variables:

$$\pi^* = \int \big(P_q, C, W, S, P_x, P_L, P_k, P_{ir}\big) \qquad (2.2)$$

In a perfect competitive market for land, where free entry and exit exists, an excess or profit will be driven to zero. As a result, the land rent will be exactly equal to the net income per unit of land (Mendelsohn, Nordhaus and Shaw 1994, Ricardo 1817). The Ricardian function of net income describes crops related to exogenous variables such as temperature and precipitation. More specifically, equation 2.2 captures the locus point of maximum profits for each temperature and precipitation level. It is estimated across production and factors of production indicating the net effect of changing climatic variables. The method automatically captures adaptation and inherently conceptualizes the climate model. The farmers are assumed to choose adaptation in respect to attaining the highest profit (Mendelsohn, Nordhaus and Shaw 1994). The model was developed to explain the variation in land value per hectare of cropland over climatic zones. In some countries, land markets do not function properly. In this case, net revenues per unit of land have been used instead of land values. In most cases the Ricardian response function has been used in a non-linear, quadratic functional form (Wang et al. 2009).

Wang et al. (2009) specify the model to capture the expected non-linearity relationship between net revenue and climate. They examine the impact of climate change on agriculture in China as follows:

$$V = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 P + \beta_4 P^2 + \sum_i d_j Z_j + \varepsilon \tag{2.3}$$

where, V, as the dependent variable, is the net revenue per unit of land; the variables T and P are the vectors of temperature and precipitation; Z is a vector of the county, village, household-specific socio-economic and soil type variables; the parameters β_k and d_j are vectors of the co-efficients to be estimated and ε is an error term. Based on the model, marginal impacts of climate variables T and P would be calculated as:

$$\frac{dV_t}{dT} = \beta_1 + \beta_2 \bar{T} \tag{2.4}$$

$$\frac{dV_t}{dP} = \beta_3 + 2\beta_4 \bar{P} \tag{2.5}$$

The Ricardian approach has been used both for developed and developing countries in a wide range of agriculture impact analyses. As pioneer of the Ricardian approach, Mendelsohn offers findings from farm-level to district-level data. His impact analysis study focuses on Brazil and India. He finds that within the countries there is a high heterogeneity of estimated impacts. The impact of warming could be beneficial or harmful according to the regional weather system (Mendelsohn 2009).

Mendelsohn, Nordhause and Shaw (1994) and Mendelsohn et al. (2007) studied the impact of increased inter-annual variance in temperature on land values. They observed that impact depends on the timing of climate shocks: increased variance in spring or summer tends to reduce land value as farmers do not have the adaptation option to change cultivation. On the other side, winter temperature variation will increase the economic value of land as farmers can adjust their production plan.

Finally, they specify the econometric model as follows:

$$V_n = \alpha + \sum_{i=season}[\beta_i T_i + \gamma_i T_i^2] + \sum_{i=season}[\delta_i P_i + \theta_i P_i^2] + \sum_k \varphi_k G_k + \varepsilon \tag{2.6}$$

where, V_n as the dependent variable, is the net revenue per unit of land; the variables T and P are the vectors of temperature and precipitation; G represents a set of socio-economic variables; α is the intercept; β_i , Υ_i, δ_i and θ_i , φ_k are vectors of the co-efficients to be estimated; i is the season and ε is an error term.

The impact of climate change is estimated by the change in land value. The change in land value ΔV resulting from one climate period to another under different global emission projections can be estimated as follows:

$$\Delta V = V_{land}(C_L) - V_{land}(C_M) \tag{2.7}$$

where L and M represents different climate change parameters and related trajectory. More specifically it would be land value related to temperature regimes. With the same procedure, the land valuation or net farm income of the same farmer could be measured for threshold, non-adapted and adapted at different climate parameters. If the climate change parameter has negative impacts on land value or productivity per unit of land then the net change will be a welfare loss. In agriculture, the total welfare loss is calculated from the area of land and net effects per unit of land.

This approach also performed suitably for analysis of the impact to climate change on African agriculture. In the case of Africa warming harms dry land farming and reduces land value, but benefits irrigated agriculture (Hertel and Rosch 2010).

In view of a decade-long efforts working with the Ricardian approach in developing countries, Mendelsohn states:

"The studies generally confirm the hypothesis that tropical and subtropical agriculture in developing countries is more climate sensitive than temperate agriculture. Even marginal warming causes damages in Africa and Latin America to crops. Crops are also sensitive to changes in precipitation. In semi-arid locations, increased rainfall is beneficial. However, in very wet places, increased rainfall can be harmful. If climate scenarios turn out to be relatively hot and dry, they will cause a lot of damage to farms in low latitude countries. However, if climate scenarios turn out to be relatively mild and wet, there will be only modest damages and maybe even beneficial effects. The magnitude of the damage depends greatly on the climate scenario" (Mendelsohn, 2009).

Given the assumptions, the approach uses cross-sectional data to estimate long-run relationships of climate change and land value. It is also sensitive to the problem of the omitted variable bias because the net revenue depends on a number of factors. The empirical model formation probably cannot identify all of the variables in a model. Quiggin and Horowitz (1999) criticize the Ricardian approach for the comparative static nature of its results. According to them the approach overestimates climate impacts because the climate threshold or optimum values are either implausible or non-existent. Hence, the implications of the estimated yield and return functions must be interpreted cautiously for potential limitations. The limitations are not inherent in the approach, but rather due to the particular empirical implementation. The problem is mostly pronounced for non-marginal changes in climatic variables for short-run inter-annual variations of the variables or relevant for very long-run analysis.

Another important criticism of the approach is in the dynamics of adjustment from one climatic region to another. Such adjustments are totally ignored and the approach assumes the adjustment costs to be zero.

(b) Advanced Ricardian (panel data) approach

Overcoming the bias of the omitted variables in the Ricardian (cross-sectional) approach has lead to the use of panel data to study the economic effects of annual fluctuations in weather variables on agriculture output and profits (Schlenker and Roberts 2006, Deschenes and Greenstone 2007). Deschenes and Greenstone (2007) extend the Ricardian approach by applying panel data to US agriculture. Their motivation for using a panel model instead of the cross-sectional Ricardian approach is that the estimated value of welfare resulting from each regression varies a great deal across time. Only considering cross-sectional estimates will allow them to capture the true affects. This approach by Deschenes and Greenstone (the DG approach) is also criticized as it focuses on short-term weather fluctuations rather than on climate change. Farmers are adapting alternative practices not only for short-term weather variability but to cope with long-term climate change (Massetti and Mendelsohn 2011). In a panel Advanced Ricardian (panel data) model repeated independent cross-sectional data is used (Mendelsohn, Nordhaus and Shaw 1994, Mendelsohn, Dinar and Sanghi 2011, Schlenker, Hanemann and Fisher 2006, Massetti and Mendelsohn 2011). The empirical model is represented by the following:

$$V_{i,t} = X'_{i,t}\,\beta_t + Z'_i\gamma_t + C'_i\varphi_t + \mu_{\prime,t} \tag{2.8}$$

where $V_{i,t}$ is the value of land per unit for the farm i at period t; $X'_{i,t}$ is the vector of time-varying variables; Z'_i is the vector of time-invariant variables; C'_i is the vector of climate variables; the β_t γ_t and $\varphi_t$are the co-efficients which are allowed to change to over time. Massetti and Mendelsohn argue that this panel model is mis-specified because the co-efficients of time-varying variables should not be changed over time without any evidence of structural change, and the co-efficients of time invariant variables should not change unless there is a structural shift in the economy. Hence, they improve the original Ricardian model by considering heterogeneity in the cross-sectional model (Massetti and Mendelsohn 2012). They specify the Ricardian model as follows:

$$V_{i,t} = X'_{i,t}\beta + Z'_i\gamma + C'_{i,t}\varphi + \mu_{\imath,t} \tag{2.9}$$

where β , γ, and φ are time invariant vectors. They apply two ways to estimate the Ricardian model with panel data. The first way is to pool the entire data set and estimate the specified model (2.8). The second way is to estimate two stages (Hsiao 2008). In the first stage, land value is regressed on the time-varying variables using the covariance method with county (group) fixed effects and weights equal to farm land in each county represented as follows:

$$V_{i,t} = X'_{i,t}\beta + \alpha_i + \varepsilon_i \tag{2.10}$$

where ε_i is the error term and α_i is the intercept. This fixed effect in the first stage controls omitted spatial variables. In the second stage of the so-called Hsiao model, the time-mean residuals are regressed on the time-invariant variables using Weighted Least Squares (WLS), with weights equal to the average farmland in each country over the observation period.

There are two versions available for panel data estimates, namely the fixed-effect model and the random-effects model (Baltagi 2008). The fixed-effects model has the power of controlling time-invariant farm-specific variables and the unobserved effects of soil conditions, labor and fertilizer availability, and access to social capital and farmers' skills (Barnwal and Kotani 2010). It offers better estimates if the assumptions of robustness are fulfilled in the model specifications. The STATA statistical software directly ensures a robust fixed-effect model and it can be used to test whether or not there is change over the period of time within the co-efficients of time-variant or invariant variables.

2.4 Climate change impact, vulnerability and adaptation studies for Bangladesh

Bangladesh is one of the world's most vulnerable countries to climate change. The vulnerability of all economic sectors is frequently cited by the climate change monitoring authority (Pervin 2013). Interestingly, studies on the impact of climate change on farming are very limited despite the farming sector being the country's second largest sector and one that is under the threat of climate change. Some rudimentary studies of the farm economy have been conducted focusing on climate shock perspectives. The climate change studies on agriculture conducted in Bangladesh can be categorized into simulation modeling studies and descriptive studies Sarker (2012).

2.4.1 Modeling studies

CEGIS assesses climate change impacts, vulnerability and adaptation for sustainable rice production in Bangladesh (CEGIS 2013). It focuses on different climatic scenarios and uses a hydrological model that it developed and set up to assess water availability in different climate change scenarios. Different response measures are identified for scenario development, and the hydrological model (SWAT) sets up data derived from climate and hydrological data and data on water availability. The SWAT model was calibrated and simulated for two climate change scenarios: A1 and A2 (for the periods 2011-2040, 2041-2070 and 2071-2100). It found that there was an increase of water availability during the wet season while availability decreases in the dry season. The model results are utilized to generate crop yield information and to assess food security in different climate scenarios.

Mahmood (1997) analyzed the effect of temperature fluctuations on *Boro* rice using the YIELD model for 12 greater districts of Bangladesh. The relationship between temperature variations and different crop growth stages were assessed in the study. The relationship was non-linear for early growing stage and linear for other stages. Interestingly, higher temperatures and evapotranspiration caused yield losses (Mahmood 1997).

Islam et al. (2014) assessed the vulnerability of fishery-based livelihoods to the impacts of climate variability and change in coastal areas of Bangladesh. They used a composite index approach to calculate vulnerability in a qualitative manner to understand how exposure, sensitivity and adaptive capacity can be measured. They found that exposure to flood and cyclones, sensitivity in livelihood and adaptive capacity are main factors of vulnerability.

Rayhan and Grote (2010) estimated the vulnerability of flooded farm households using the expected poverty vulnerability method and a cross-sectional survey of 1050 rural households. They estimated that 58 percent of flooded rural households were considered to be poor and 67 percent were considered to be vulnerable. The study also suggested that a mixed cropping system associated with crop diversification in rural Bangladesh may reduce farm household vulnerability.

Azam and Imai (2009) estimated ex-ante poverty and vulnerability of households using the Income and Expenditure Survey (HIES) 2005. The study found that agricultural households are likely to be the most vulnerable, and the coastal area is more vulnerable than the other regions. The study did not link the spatial or inter-temporal variation of income vulnerability to climate variability.

Sarker (2012) conducted a study on the impacts of climate change on rice production and farmers' adaptation in Bangladesh. To better understand the climate change problem, the study examined farm-level micro data that focused on the impact on crop production and investigated the variations of rice production due to climate change at the farm-level. The econometric analysis was done to identify social, demographic and institutional factors contributing to farm profit under changing climate conditions. Both mean and median regression was applied to empirically assess the possible determinants of farm revenue from rice production. Sarker (2012) also estimated the economic impact of climate change on rice yields using cross-sectional time series data. Just-Pope production function was used as the theoretical framework. The study found that the impact of climate change stimuli varied among the three growing seasons. Maximum temperature was positively related to mean rice yields of the *Aus* and *Amon* season in the linear model, while negatively related in the quadratic model. The production elasticity values imply that maximum temperature increases risk for Aus and Amon rice, but reduces risk for the *Boro* growing seasons. Finally, the impacts of rainfall on yield variability were positive for the *Amon* season and negative for the *Aus* and *Boro* growing seasons. The results imply that rainfall increases risk for the *Amon* season but reduces risk for the *Aus* and *Boro* season. The study also estimated future yields of rice for three periods (2030, 2050 and 2100) and scenarios using proportionate change in maximum temperature, minimum temperature and rainfall. In addition, the determinants of farmers' adaptation options by perceived climate change were analyzed. The study conducted brilliant and methodological research work in the field of climate change impacts on rice farming in Bangladesh. But it did not capture the dynamics of adaption options in the model of climate change impacts. In reality, farmers are operating farm activities under climate change and associated adaptation options. The whole analysis of the economic performance needs an integrated assessment approach.

2.4.2 Descriptive studies

Rasel et al. (2013) assessed soil and water salinity effects on crop production and adaptation strategies for the coastal area of Bangladesh. The study presented a scenario-based descriptive analysis of salinity in different seasons. They found that salinity causes an unfavorable environmental and hydrological situation. In the dry season, the unfavorable environment restricted normal crop production, while in the rainy season surface soil salinity was reduced and its effect on crops was diminished.

Rashid et al. (2009) focused on the different types of vulnerability profiles for selected agro-ecological zones and climate hazards in Bangladesh. The study explains the status of vulnerable people in Bangladesh living in different hotspots that faced climate change related disasters, such as rising sea level, salinity, cyclones, storm surges, floods, flash floods, river bank erosion, and drought. The scenario development workshop in the study identified vulnerable people which included small and marginal farmers and agricultural wage workers.

Rashid and Islam (2007) analyzed adaptation to climate change for a sustainable development of agriculture in Bangladesh. The study focused on different adverse effects of climate change in different sub-sectors of agriculture by using descriptive measurement. For coping mechanisms the study suggested some adaptations that could be used for protecting against climate shock in farming, such as quick harvest and seeding, intercultural operations, irrigation water management, and disease and pest management.

Rawlani and Sovacool (2011) in their study, claim that agriculture is one of the six sectors in Bangladesh that is vulnerable to climate change. The study revealed that climate change vulnerability could be reduced by multiple and integrated adaptation strategies in agriculture.

Ali (1999) assessed extreme climate change events such as cyclones, storm surges, coastal erosion and rising sea levels, and the resulting consequence of the loss of agricultural land in eastern Bangladesh. The study identified that public and private adaptive measures such as embankment construction and farm-level introduction of new saline and temperature-tolerant varieties could be a solution.

2.5 Intermediate conclusion: theoretical and empirical implications of climate change and adaptations on farm economics and the research gap

A number of articles have been written about the effect of climate change on agriculture. Research on the assessment of the climate change impact on agriculture has received a special attention since the first IPCC report in 1990. However, economic assessment of farm-level adaptation to and mitigation of the effects of climate change still has been neglected. Understanding the links between the climate system, farming systems and the economic framework is important for knowledge synthesis and policy-making. In this chapter, insights from available economic literature and the current state-of-the art in evaluating farm-level adaptation options are discussed. In so doing, the chapter reviews different approaches on the impacts of climate change on agriculture and the specific limitations on the analysis of adaptation were critically evaluated.

The impacts of climate change and adaptation are complex and constitute a multi-disciplinary phenomenon. In addition, different components of agriculture and crop categories are affected in different ways by climate variability and change (Deressa, Hassan and Poonyth 2005, Isik and Devadoss 2006). The effects of change also vary in spatial bio-physical environments. Existing studies are not focused on individual crops, nor on AEZ specific effects. Some studies on agronomic effects use yield response models. But the whole story of the economic impacts of climate change should focus on historical farm-level vulnerability of income, the impact on farm net income, and the assessment of the dynamics of adaptation options by economic cost and returns analysis.

From the above reviews of literature, it can be said that some cross-sectional time series observation framework for the impacts of climate change and the assessment of adaptation options has been developed. But most of the studies apply the panel econometric framework on agriculture as a whole and are not crop-specific models.

In Bangladesh there is little evidence of the assessment of the panel impact of climate variability and change. Interestingly, a number of descriptive studies have been conducted on climate change on agriculture, but these studies have not been extended by any econometric framework or statistical inference.

Therefore, the present study assesses farm-level climate change impacts with different frameworks of adaption impact assessments and appraisals in an integrated way using panel data both for descriptive and econometric inference.

The link between climate change and farming systems is vital in forming effective policy. Investment decisions depend on crop yields, and their vulnerability and the impacts of climate shocks on farm earnings. In a changing climate system, farmers try to adopt new practices. Under new adaptation practices farms are operating and investing with uncertainty. It is likely to be challenging to conceptualize the adaptation to climate change from an agricultural perspective within economic theory and empirical analysis.

The economics of production and farm management analytical tools are fundamental for farm-level climate change impact and adaptation assessment. Most of researchers have considered Ricardian theory of land rent as an acceptable basic theory for climate change impact analysis in agriculture. But land valuation does not always reflect productivity. Therefore a combination of a crop yield approach, an integrated farm net income assessment approach in addition to the classical theory of land rent will offer a solution for assessment of farm-level climate change adaptation options.

Farm-level adaptation strategies need basic supportive research to develop and sustain technologies. Research on resilient farming systems and their management are important in analyzing tradeoffs between efficiency and resilience. The evaluation of climate change mitigation technologies such as System of Rice Intensification (SRI), crop rotation, and use of non-tillage cropping systems is necessary in on-station and on-farm research. The assessment of mitigation policies at the farm-level and their efficacy with private and public decisions could be a pathway to future research.

3 Methodology

3.1 Introduction

This part of the study provides the methodology for the research. It discusses the design of the farm survey, the process of data collection, and sources and outlines the tools and techniques to analyze the data according to the study's objectives. The basic analytical part of the study consists of three stages: (1) Descriptive analysis of the options for farm-level adaptation to climate change, (2) economic implications of adaptation options using farm management performance analysis for different climate thresholds, and (3) the assessment of the impacts of climate change and adaptation using the latest structural Ricardian approach. The patterns and extent of adaptation and its impact on farm income are examined at the micro level. This is an important aspect of the analysis which is based on an intensive farm survey and integrates the relevant findings from existing literature, expert opinion and secondary data sources. The details of the farm household survey are presented in the next section.

3.2 Farm survey

A survey is a widely-used technique of primary data collection. Setting objectives, interviewing relevant respondents by structural questionnaire or survey schedule is a common feature of survey design (Dillon and Hardaker 1980). For the present study, an intensive farm survey was conducted in two phases to obtain relevant farm data from 2006 to 2013. In the first phase, three hundred climate-prone sample farmers were interviewed through trained enumerators, over the five month period of February to June 2011. Details from respondent farmers of farm input and output data of the *Boro* and *Amon* rice growing seasons from 2006 to 2011 were recorded in the survey schedule (see appendix-1). In the second phase, the same sample farmers were interviewed again in the same manner over the two month period of mid-June to mid-August 2013. The second phase interviews helped to update data of yields and input-output relations of rice farming recorded from 2011 to 2013. As a result, eight years of panel data from the farm-level was generated to fulfill the objectives of the research. The farm production information and related data for 2006 was considered as a farm-level situation threshold. The data for 2007 to 2009 was considered a period of climate shocks for the same sample farmers. Finally, 2010, 2011, 2012, and 2013 were considered an adaptation period for the farmers as they started alternative production management under climate change. The direct interviews provided data for *Boro* production up to mid-May 2013, and for *Amon* up to December 2013. The input-output data of the latest *Amon* season rice was collected by phone to complete the panel.

Before conducting the survey, a draft schedule was designed and pre-tests were carried out to check for the suitability of the schedule at the field level. Then the final survey was compiled according to the data needed for each objective of the study. The schedule has eight main sections. The first and second sections are related to farmers' identification and profiles, including information about farm size, family size, land tenure systems, physical assets, social capital and access to basic facilities. The third section is related to land utilization patterns for different crops and other activities. In order to obtain agro-climatic variability data, the information in the fourth section was collected monthly. Section five provides the place for agro-economic information of different crops according to the crop growing season. The format of this section is broad and elaborative having comparative information of the threshold, the non-adapted and adapted periods, and the input-output relationships of different crop patterns. The study found only two basic cropping patterns of rice, namely *Boro*-Fallow- *Amon* and Fallow- *Amon*-Fallow, over the period. Section six provides the data for weather and climate variability shocks. Sections seven and eight provide farm-level adaptation information, farmers' perceptions, and constraints of adaptation.

3.2.1 Selection of the study area and sampling

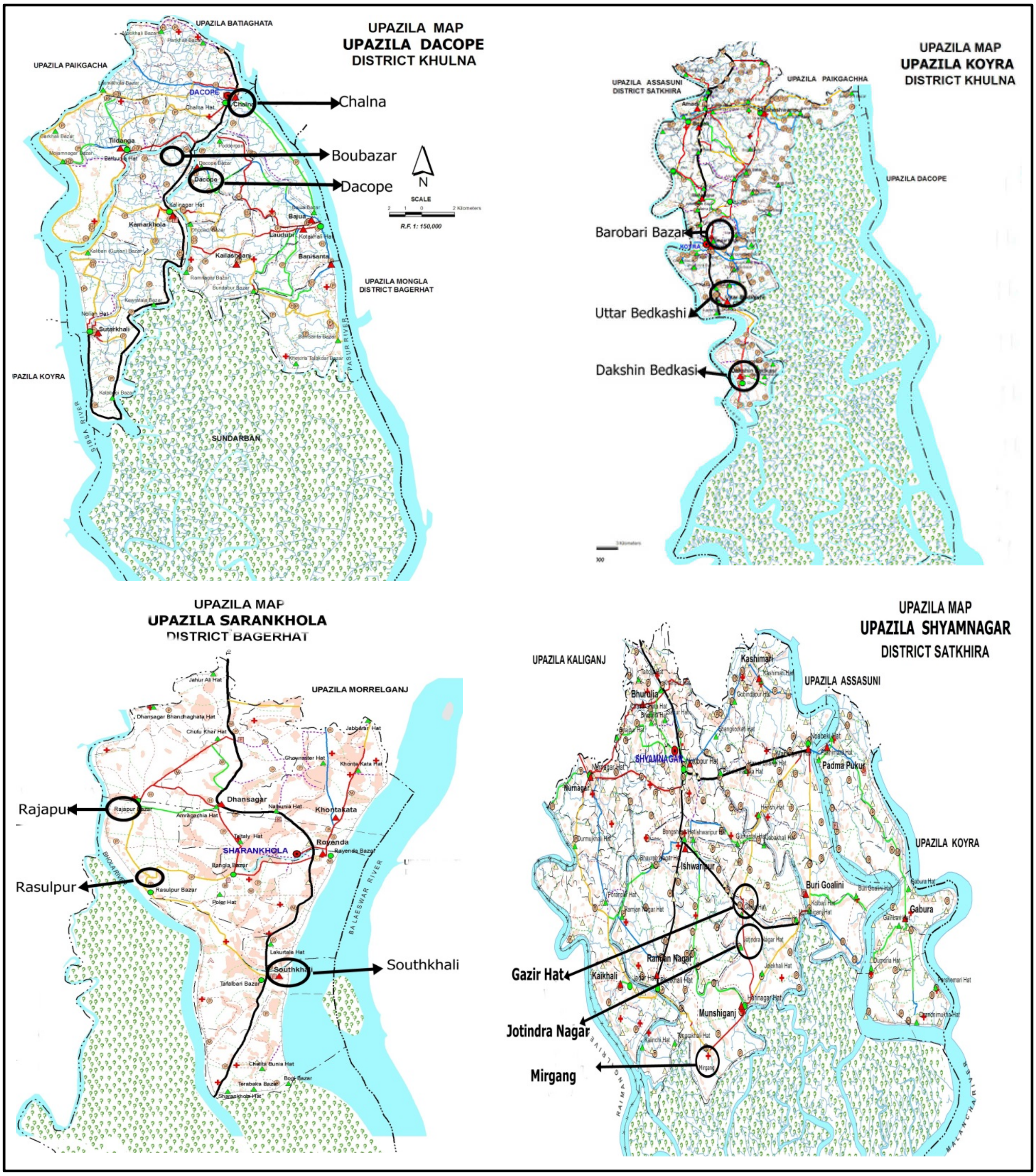
It was purposively decided that farm survey data would be obtained from three southwestern coastal districts of Bangladesh. The study areas were Khulna, Sathkhira and Bagherhat districts with 13 agro-ecological zones where tidal floods come through cannels twice a day from the sea. From the three districts, four *Upazila* (sub-district) were also purposively selected for the study. The selection of the locations depended on the extent that climate variability had been realized and alternative adaptation to climate change had been practiced by farm households. The initial step was to select districts which were predominantly known as climate-prone areas and had experienced high-temperature shocks, erratic rain-fall, seasonal drought, and salinity intrusion from rising sea levels. In addition to this, farming in the area was severely affected by climate variability and shocks from 2007 when a sea storm, *Sidre,* devastatingly flooded and damaged crops. Since then, the existing production system has been difficult to operate profitably because of the bio-physics of the soil changes. Subsequently, another cyclone, *Aila,* catastrophically hits the agricultural production system of the area in 2009.

As a consequence, the same land is no longer productive at the historical threshold level and frequent climate events lead to farm operation with alternative management. Since 2010, the selected areas have been covered by the climate change adaptation program of two non-government organizations (NGOs), *Shushilon* and *Prodipon* and the government of Bangladesh (GOB) Department of Agricultural Extension (DAE). Additionally, the opinion of experts in climate change shocks on farming was important in selecting the areas.

Figure 3.1 Political map of Bangladesh

Source: The National Encyclopaedia of Bangladesh (Banglapedia 2013)

Figure 3.2 Study sites



Source: The National Encyclopaedia of Bangladesh (Banglapedia 2013)

3.2.2 Sampling design

A multistage sampling technique was used in selecting the farm households. In the first stage, three villages from each *Upazila* were randomly selected. The farmers selected were those in the 12 villages who had adapted to climate change and participated in the DAE's program for climate adaptation. From each village, 25 adapted farm households were randomly chosen for better representation of the population. In total, 300 adapted farm households were selected for the study which is a relatively small sample size compared to the size of the population. However, for the similarities in the socio-economic, agro-ecological zones, and production environment, the small sample size is considered a valid representation of the whole population (Gilbert 2008, Blaikie 2010).

Table 3.1 Distribution of sample farms by location and group

District/*Upazila*	Number of sample villages	Number of sample farm per village	Total number of sample farms
Khulna			
Dakop	3	25	75
Koyra	3	25	75
Sathkhira			
Shamnager	3	25	75
Bagherhat			
Soronkhola	3	25	75
Total	12	-	300

Source: Author's survey

3.2.3 Other data sources

The climate data on monthly maximum and minimum air temperatures and rainfall for 1986-2013 was collected from the nearest weather stations (Sathkhira and Mongla) and the Bangladesh Agricultural Research Council (BARC)'s web-site. Daily and monthly data were converted to seasonal averages according to the major rice growing seasons *Amon* and *Boro.* In addition to this data, the study used published and unpublished statistics and information of different research articles and organizations, including internet sources. The notable sources are the Bangladesh Ministry of Agriculture, DAE *Upazila* Agricultural Office, Bangladesh Metrological Department (BMD), Bangladesh Rice Research Institute (BRRI), Bangladesh Bureau of Statistics (BBS), IPCC and FAO. Expert opinions and field-level experience of officials and academics also provided information that helped to check the consistency of the collected data.

3.2.4 Data coding, entry and cleaning

The collected data was coded for entry into a Microsoft Excel spreadsheet before being converted to STATA program. Entries were first made according to regions and then pooled according to the analytical framework. The data was cleaned by producing frequency distributions and examined for outliers. When data was found to be consistent, it was then prepared for further analysis.

3.3 Data analyzing methods and instruments

The study applied different analytical methods and instruments according to its different objectives. Survey data was arranged and analyzed in four categories. Some instruments were qualitative or narrative, some used tabular form for descriptive statistics, and the remaining tools were econometric modeling. The statistical and econometric modeling instruments also use different test statistics tools for validating the estimates. The instruments are explained below and further explanations are presented in specific relevant chapters.

3.3.1 Instruments for insight into adaptation practices

This part of the thesis used only tabular information of survey data with preliminary statistical instruments: mean, standard deviations, maximum or minimum, frequencies and percentages of different information. The qualitative assessment of adaptations was done by using expert opinion, internet sources and published documents about low-carbon farming. In addition to this some pictorial presentations are applied as instruments to describe the nature of the adaptations.

3.3.2 Instruments for economic implication analysis

To examine the economic implications of adaptation strategies, data from the field survey was used to analyze different farm management analytical tools such as gross margin analysis, net margin analysis, and partial budgeting, and productive capacity analysis of land. The study used the threshold situation as reference for comparison. The farm-specific indicators were presented using descriptive statistics such as mean, standard deviations, co-efficients of variation, and the mean difference for testing whether farm performance changes are statistically significant at different thresholds. Moreover, adaptation practices are appraised on the basis of simple benefit-cost ratio (BCR) analysis and cost-effective analysis.

The benefit-cost ratio analysis (BCR) is an instrument to determine options that provide the indicator of best approach for the adoption according to financial benefits in labor, time and cost savings technique. The simple mathematical formulation of BCR as follows:

$$BCR = \frac{\sum_{i=1}^{n} \frac{b_i}{(1+r)^i} + \frac{R_n}{(1+r)^n}}{A + \sum_{i=1}^{n} \frac{c_i}{(1+r)^i}} \tag{3.1}$$

where, b_i is the benefit in the ith year; R_n is the replacement value for n (years) of life span; r is the rate of interest; A is the initial investment; and c_i is the maintenance cost in the ith year. A preliminary criterion of appraising adaptation options by the BCR analysis is that the value of BCR being greater than one implies a success in the adaptation practice, as it would be financially feasible.

Cost-effective analysis (CEA) is a form of economic analysis that compares the relative cost and outcomes (effect) of two and more courses of action. The CEA is expressed as a ratio where the nominator is the gain of an alternative production practice from a particular measure (for example, the quantity of the product protected from climate change shocks, saving of resources, quality gained) and the denominator is the cost associated with the measure. In this study, the CEA represents the appraisal of adaptation by quantifying the rice output gained for each 100 BDT spent on the specific adaptation. This is also compared with the price of one kilogram of rice. The criterion for a successful appraisal is the output gains or quality gains under new adaptation and climate change dynamics being higher than the associated cost of the adaptation.

3.3.3 Method of analyzing the impact of climate variability and adaptation options on agriculture

For assessing the impact on agriculture, the study first applied the advanced Ricardian model with some modifications using panel data. The revised model was fitted to investigate whether climate variability and adaptations have any impact on farm net income. Other modifications use climate variability parameters instead of long-term climate change variables. In addition to these, the study fitted the log-linear fixed-effect panel model for specific crop rice in two growing seasons. In tropical and sub-tropical countries the climate variable temperature has an adverse effect when it reaches up to 30^0C. Therefore, instead of using average temperatures, the study used average maximum temperatures. The usual Ricardian model is set the relationship of temperature and rainfall to land value in a quadratic form. In the present study, the relationships of farm net income to climate factors, adaptive capacities and the variables of other idiosyncratic farm characteristics were assumed to be of log-linear form. The functional relationships were validated by the Box-Cox test that ensures the linearity of the estimated equations and log-linear specifications.

The study also performed some post-estimation tests, including the Hausman-test, the test for cross-sectional dependency and the heterocadasticity test. Hausman-test helps to decide whether a fixed-effect model or a random-effect model should be used.

The marginal impact of climate variability and adaptation options was simulated from the estimated co-efficients of the fixed-effect models with future climate change scenario. The study applied simple Microsoft Excel spreadsheet calculations for the future net income path relating to changing climate. The estimated climate change path of net farm income was calibrated over a long period of time.

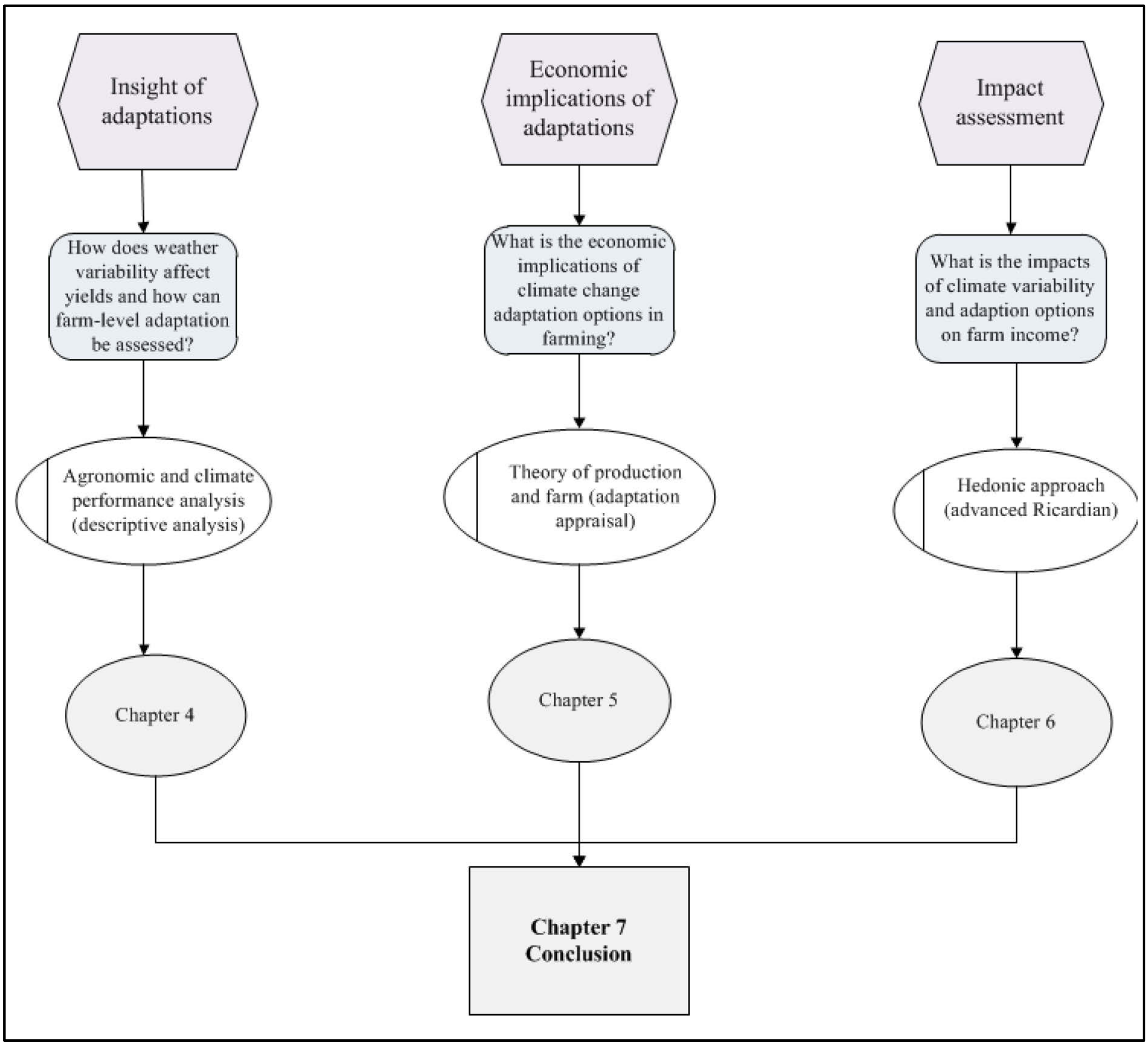
3.4 Research design overview

The research design overview in figure 3.3 relates the research questions to the analytical framework and tools. It sets out a matrix of research questions, relevant theories of analysis, and the specifications of the chapters.

3.5 Intermediate conclusions

This chapter provided the methodological framework after having reviewed the research gap in the existing literature. Farm-level climate change and adaptation impact assessment needs an integrated evaluation of climate physics, bio-environment, an agronomic background, and an economic framework in which the farming activities take place. The climate variability is a proxy for the real climate change analysis. An in-depth study of the impacts of climate change and adaptation options should be a combination of farm management and production theory, and land rent theory. Therefore, the present study applied three key components of analysis including descriptive statistical analysis and econometric modeling to get an in-depth story of the facts. The econometric models are based on the fixed-effect panel approach.

Figure 3.3 Three-tier integrated assessment approach based on farm-level panel data



Source: Author's own elaboration

4 Insight into the micro level adaptation practices to climate change: the case of rice farming in the coastal areas of Bangladesh

This part of the study focuses on insight into the adaptation practices to climate variability in the rice farming of coastal Bangladesh. The negative impact of climate change prominently appears in farm productivity. Farmers' perceived knowledge of climate variability and the related risks compels them to operate farms under alternative production practices. These alternative production practices have scientific merit and agronomic potential. But only few studies currently focus on the micro-level analysis to get insights into the potential of autonomous adaptation. Conducting an intensive survey of 300 rice farms, this study details the inside story of alternative production practices based on adaptation performance and mitigation potential. Using simple descriptive statistics and tabular analysis, the study depicts the current status of climate shocks, alternative production options and production risk. The qualitative analysis of farm activities under climate risk clearly indicates production vulnerability to climate variability and shows different adaptation options that successfully address this problem. Alternative systems also contribute to low-carbon farming for climate change mitigation.

4.1 Introduction

Climate change is a global problem originating from atmospheric CO_2 and other GHG concentrations as a result of human activities (Hertel and Rosch 2010). Over the last twenty years this has been a major global concern and developing country's production sectors have become worried about the disastrous consequences of climate change especially for agriculture (Sarker 2012). Farming is extremely susceptible to climate change as the production system depends on the natural environment. The vulnerability of farm productivity and food security to climate change has raised questions for policy-makers and researchers about the capacity of the farmers to adapt at the micro-level (Reid et al. 2007, Mertz et al. 2009). Despite decades-long scientific research the impacts of climate change on agriculture, the evaluation of farm-level autonomous adaptation to climate change remains widely un-touched. The current knowledge is mostly based on station-oriented research and crop growth simulation that was presented in chapter two in details under review. Therefore, an assess-ment of the impact of different climate parameters (temperature and precipitation) in the field is a new challenge. Farm-level adaptation to climate variability or change implies maintaining bio-logical diversity under adverse shocks. A multi-year analysis of farmer-managed fields would provide an opportunity to study how weather variability affects the yield. And long-term farm income development under climate change could help to get farm level adaptation information.

These were the basic motivations for gaining insight into the micro-level adaptation practice to in the rice farming of coastal Bangladesh. It is a country that is highly vulnerable to climate change because of its geographical location in the tropics, low elevations above sea level and high frequency of sea storms and the associated salinity intrusion. The country suffers regular extreme climate events such as high temperatures, seasonal drought, and cyclones. These occur almost every year and affect the crop agriculture sector, particularly rice production, adversely (MOEF 2005, Yamin, Rahman and Huq 2005). Overall, farmers' appear to have limited adaptive capacities because of poor economic conditions, but they are motivated to change their farm practices to deals with climate shocks.

The basic approach of the study was to identify the responsiveness of farm productivity in relation to climate shocks by analyzing farm production information. More specifically, the relative sensitivity of rice yields to climate variability and the net productivity of rice farming was analyzed, focusing on temperature and precipitation change. In addition, farm productivity data panels were used to compare threshold production, climate shocks period production and adapted period production. The results are presented by tabular and descriptive statistics using figure and fact analysis.

4.2 Current status of climate shocks and production

Agriculture, a primary sector, is one of the biggest sectors in the Bangladesh economy (Bangladesh Economic Review 2012). As a single sector, it contributes 43.6 percent of total civilian labour employment, as well as a 19.29 percent share of the GDP (Bangladesh Economic Review 2012). Rice is the staple food crop and occupies 75 percent of the total cropped area of the country. There are three rice growing seasons in Bangladesh: the *Aus* season (April to July), the *Amon* season (July to December) and the *Boro* season (January to mid-May). The land-man ratio is very high; the average farm size is less than 0.68 hectare. The majority of the farmers are resource-poor; they are operating their farm at subsistence level just to have sufficient food for the family. Government policy favors self-sufficiency and food security of the country. In the last four decades, HYV technologies such as the adoption of modern seed-fertilizer-irrigation systems contributed to a doubling of food grain production. Table 4.1 represents the national production status of rice in different seasons showing continuous growth in quantity.

Table 4.1 Rice production in Bangladesh (in millions of tons)

Season \ Year	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12
Aus	1.500	1.745	1.512	1.507	1.895	1.709	2.133	2.332
Amon	9.820	10.810	10.841	9.662	11.613	13.307	12.791	12.798
Boro	13.837	13.975	14.964	17.762	17.809	18.341	18.617	18.759
Total	25.157	26.553	27.318	28.931	31.317	32.257	33.541	33.889

Source: Bangladesh Economic Review (2012)

Interestingly, the yield growth of rice has levelled-out recent years because the yield response to supplementary nutrition has declined. Soil, bio-physical and environmental degradation are, day by day, changing agro-ecological features. The profitability of rice cultivation for farms has declined with increasing production risks and an increased price of inputs. The risk arises from different shocks of natural calamities such as floods, seasonal droughts, heat shocks, salinity, and water stagnation in rainy seasons which substantially affect agricultural productivity (Rashid et al., 2009). The affects are uneven and differ from region to region. The most vulnerable is the south-western region of Bangladesh which represents thirteen agro-ecological zones (Rashid et al., 2009).

The changing agro-climate of the extended coastal area now has to face climate variability shocks. The common cropping patterns of the sample farmers in the region are found to be *Boro*-fallow-Amon or fallow-Amon-fallow. Farmer perceptions about climate change, related shocks, and perceived reasons for rice yield stagnating and decline are summarized in table 4.2.

Table 4.2 Observed shocks in rice farming due to climate variability or change according to farmers' perceptions

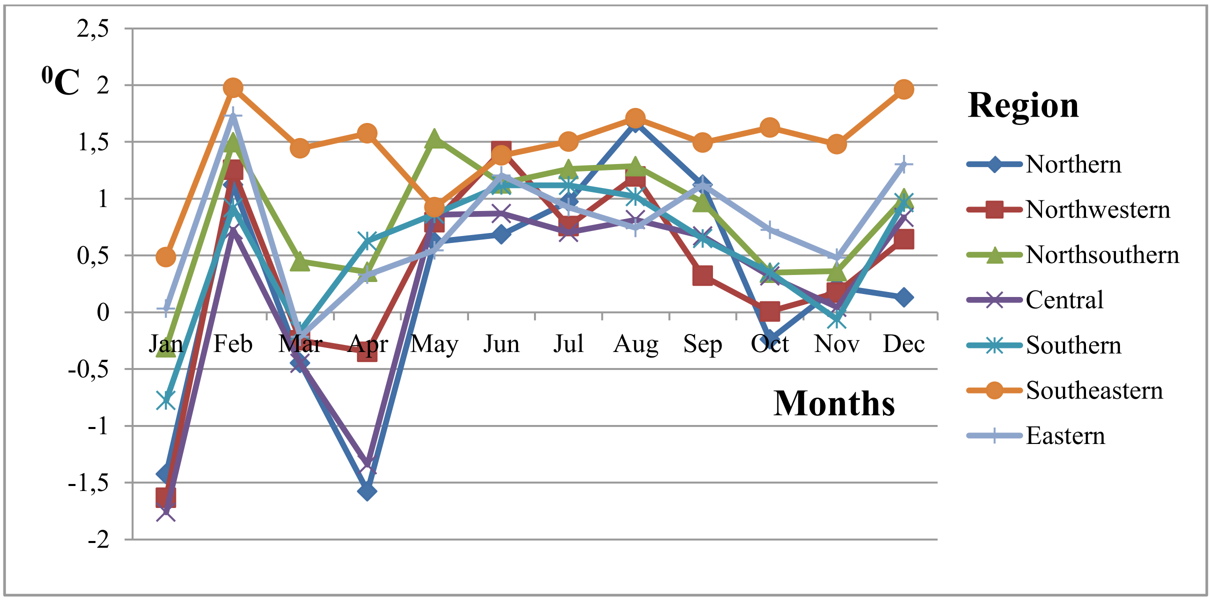
Climate change indicators	Shocks in rice farming according to farmers' perceptions	Scientific background
CO_2 emissions	No basic idea about relationship between CO_2 emissions and climate change and the associated effects on yield.	CO_2 emissions positively help yield growth as they provide flowering and grain-filling.
Temperature	During the vegetation stage, high temperatures reduce tiller numbers and plants. Lowering grain weight, proportional increase of chalky rice and milky white rice.	It speeds up crop development and shortens the duration of growth which affects productivity adversely.
Precipitation	1. Low and less-frequent precipitation in the *Amon* season delays the transplantation, delays the production cycle and lowers the yield. On the other hand, heavy rainfall at the flowering stage damages the grain. 2. High precipitation at the reproductive stages causes pests and disease infestation when it is associated with high temperature. The BLS disease spreads in epidemic proportion when conditions of high temperature and high moisture exist. 3. In the winter or summer seasons, less precipitation increases the budget of irrigation for *Boro* cultivation. Sometimes high evaporation creates moisture stress in the soil and affects the fertility.	1. Reduction of spikelet fertility and panicle exertion. 2. Changing the weed ecology and evolution of the species. Diseases rice blast sheath and culm blight become more widespread. 3. The reduction in precipitation increases the amount of water needed for plant transpiration.
Rising sea levels, associated tidal floods and salinity	1. Salinity from irrigated water seedlings turn into a grey color. The plant becomes weak, lowering tiller numbers and is finally burnt. For the *Boro* season, saline water irrigation causes insect attacks at the mature crop stages. 2. Less rain associated with salinity, is severe in production because the rain washes out the salinity in the *Amon* season. Less frequent rain restricts the operation in time.	1. Salinity in the soil causes an unfavorable bio-physical environment that hampers normal crop growth. The maximum tolerance of HYV rice is 4ds/m; beyond this level, crop physiology is totally damaged. 2. Salinity decreases terminative energy and germination rates

Source: Farm survey and author's elaboration

4.3 Indication of climate change and agricultural production

The monthly average maximum temperature of Bangladesh has changed over the period from 1976 to 2008. Figure 4.1 depicts the magnitudes of changes in monthly average maximum temperature per year compared to 1975 which is positive for most of the regions. For this period, Basak, Titumir and Dey (2013) conducted an assessment of maximum monthly average temperatures by using trend analysis for different regions of Bangladesh. Except for January and April, monthly average maximum temperatures follow an increasing trend for most of the regions over the period, as shown in figure 4.1.

Figure 4.1 Changes in monthly average maximum temperatures per year from 1976 to 2008

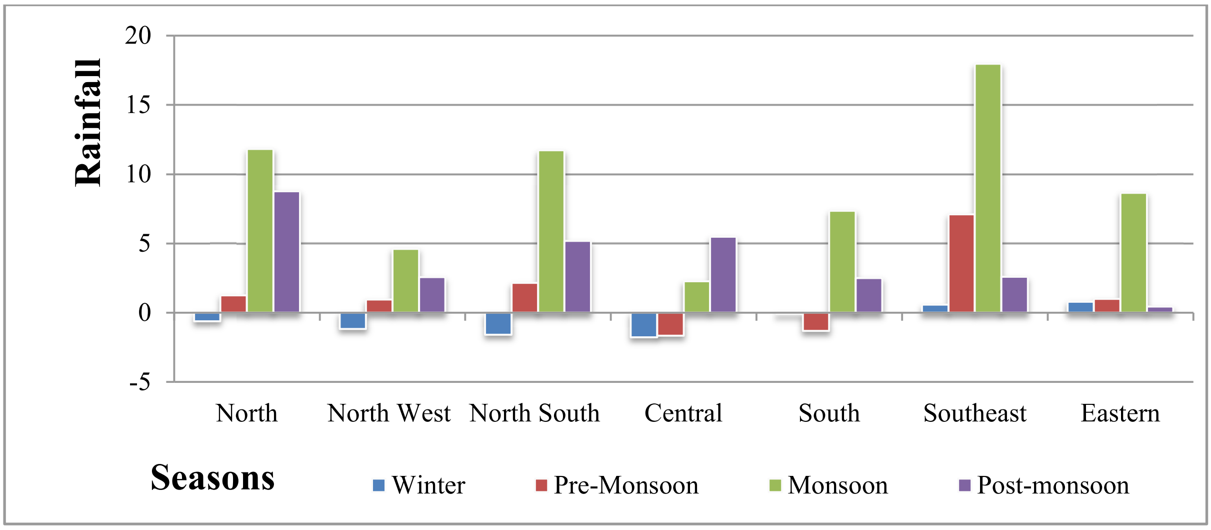


Source: Basak, Titumir and Dey (2013)

The largest changes were found in the southeastern region. The study area is in the northern part of the southern-region where the changes in average monthly maximum temperature were always positive, except for January (Basak, Titumir and Dey 2013). There is a clear indication of long-term seasonal temperature changes all over the country.

Changes in rainfall are positive for most seasons, except for the pre-monsoon season in the southern region. The winter and pre-monsoon seasons in the central region, and the winter season in the north, northwest and north-southern region are shown in figure 4.2.

Figure 4.2 Changes in rainfall (mm) across four seasons (per year) from 1976 to 2008



Sources: Adapted from Basak, Titumir and Dey (2013)

Rising sea levels also appear at different checking points of the Bay of Bengal in Bangladesh over 22 years (shown in table 4.3).

Table 4.3 Historical tidal data measuring the sea levels at three coastal stations in the Bay of Bengal from 1978 to 2000

Observation point	Location	Latitude (N)	Longitude (E)	Datum (M)	Trend (mm/year)
Hiron Point	Western	$21^{0}48'$	$89^{0}28'$	3.784	4.0
Char Changa	Central	$22^{0}08'$	$91^{0}06'$	4.996	6.0
Cox's Bazar	Eastern	$21^{0}26'$	$91^{0}59'$	4.836	7.6

Source: SMRC (2003) adapted from MOEF (2005)

According to the report of the SAARC Meteorological Research Council (SMRC), the rate at which the sea is rising in the area is higher than the mean rate of global rising sea levels over 100 years SMRC (2003).

The study area is situated at the western observation point and, according to data in table 4.3 for *Hiron point*, there is a trend in the rising of the sea level of 4mm per year.

The secondary effect of rising sea levels is salinity which occurs as a result of tidal flooding of coastal crop fields. The large area affected by salinity due to rising sea level around the study area is shown in table 4.4.

Table 4.4 Historical salinity data of the surveyed districts from 1973 to 2000

District	Salt Affected Area (000' ha)		Salinity Class (ds/m)								Change	
			S1 (2.0-4.0)		S2 (4-8.0)		S3 (8-15.0)		S4 >15.0		Area (000'ha)	%
	1973	2000	1973	2000	1973	2000	1973	2000	1973	2000		
Khulna	120.04	145.25	3.9	28.8	92.4	37.32	13.0	59.49	9.8	19.61	25.21	21.0
Bagerhat	107.98	125.13	8.3	35.7	77.8	41.5	2.6	41.23	0.0	6.74	17.15	15.9
Sathkhira	146.35	147.08	16.5	27.0	85.6	38.01	33.5	60.03	10.9	22.01	0.73	0.5

Source: Sarker (2005)

Almost all climate variability indicators in Bangladesh over the last 34 years appear to have changed. Although Bangladesh is not a big emitter of GHG, national and international researchers claim the country would be one of the worst affected by climate change and rising sea levels (World Bank 2000, Titus 1990).

Table 4.5 Upazila-wise sample farmers' yields (kg/ha) in two growing seasons from 2006 to 2013

Region \ Year	2006	2007	2008	2009	2010	2011	2012	2013
Dacop								
Boro	5,001	2,979	2,772	2,595	4,660	4,496	4,323	4,131
Amon	1,681	1,335	1,319	1,158	1,593	1,571	1,540	1,524
Koyra								
Boro	3,587	2,600	2,467	2,347	3,557	3,444	3,357	3,298
Amon	1,910	1,457	1,314	1,240	1,836	1,761	1,707	1,681
Samnagar								
Boro	4,073	2,671	2,374	2,201	3,926	3,823	3,729	3,663
Amon	2,740	2,229	2,008	1,534	2,664	2,483	2,435	2,422
Soronkhola								
Boro	3,828	2,658	2,245	2,075	3,569	3,460	3,393	3,334
Amon	3,812	2,877	2,676	2,274	3,583	2,483	2,435	2,421

Source: Author's farm survey

Only a few places in the world experience similar effects and indication of climate change. Bangladesh experiences frequent severe weather patterns, high temperatures, heavy rains, seasonal droughts, sea storms and salinity intrusion, and flooding (Titus 1990). The effect of increasing temperatures and that of decreasing precipitation on yields is negative (Karim, Hussain and Ahmed 1996).

Other threats are addressed by Huq, Ahmed and Koudstaal (1996) who stated that rising sea levels will flood more than one million hectares of agricultural land and could result in 14,000 tons of grain production being lost in the eastern region in 2030. The current agricultural production of rice is 34 million tons (Bangladesh Economic Review 2012). The average yield of rice and its development for sample farmers of the survey for 2006 to 2013 is projected in table 4.5.

4.4 Results and discussion

4.4.1 Farm profiles

The sample farms' profiles are presented in table 4.6 which mostly focuses on the general farm-level characteristics and bio-physical environment, including the climates in which the farms are operating.

The average age of the head of the farm household is 39.5 years and on average they have more than seven years schooling.

Table 4.6 Farm profiles and related variables

Variables	Mean	Std. Dev.	Minimum	Maximum
Farm size (in decimals)*	306.00	290.00	20.00	1,650.00
Age of the head of the household (in years)	39.53	11.48	20.00	78.00
Education(in years of schooling)	7.49	3.60	1.00	16.00
Family labour (persons aged between 15 and 65 years)	2.23	1.43	1.00	10.00
Soil type (five categories 1-5)	3.66	1.00	2.00	5.00
Variety dummy (HYV: yes =1, local = 0)				
Boro	0.77	0.41	0.00	1.00
Amon	0.74	0.43	0.00	1.00
Irrigation dummy (access to saline free irrigations: yes =1, no = 0)	0.49	0.50	0.00	1.00
Adaptation rank (score 0, 1, 2 or, 3)	1.20	1.33	0.00	3.00
Ratio of applied fertilizer budget to balance dose (%)	73.00	31.00	12.00	270.00
Returns to land (BDT/ha)				
Boro	20,165.00	10,602.00	23.00	58421.00
Amon	22,498.18	12,193.90	3477.76	59,724.90
Temperature (^{o}C)				
Boro	32.15	0.55	30.93	33.08
Amon	30.98	0.93	30.43	32.08
Rainfall (in millimetres)				
Boro	45.00	13.62	24.80	73.60
Amon	200.00	20.93	188.96	295.00
Price BDT/kg	13.81	1.50	12.5	16.50
Production cost (BDT/ha)	25,941.00	4,715.00	1,4187.00	5,0313.00

*247 decimals =1 hectare

Source: Author's own farm survey

On average, a sample farm family has more than 2 productive persons aged between 15 and 65 years. The average sample farm size is 306 decimals more or less corresponds to the national average. The area has five categories of soil: sandy, sandy loam, loam, clay loam, and clay. More than seventy percent of the land in the study area is clay loam soil.

The variable adaptation rank is calculated as a score from 0 to 3 by the nature of the performances of the coping practices and the combinations for mitigation and adaptation to climate change.

4.4.2 Farm-level adaptation practices and potential for a low-carbon farming technique

Adaptation at the farm level may be explained as an adjustment in ecological, social and economic systems in response to the climate variables and their effects. More specifically, adaptation practices comprise process, actions, and outcomes in a farming system for better adjustment under changing climate (IPCC 2007b).

The micro level adaptations are also an autonomous response to climate variability or change such as shocks, stress, hazard, risk or opportunities. Most of the adaptation practices have the added benefit of enhancing low-carbon farming. But the main motivation for a new adaptation practice certainly is positive impact on productivity and immediate livelihood benefits (Bryan et al. 2011, Tyndall 1996, Kiptot et al. 2007).

The sample farmers of the study participate in different GO and NGO extension programs. The two NGOs, *Shushilon* and *Prodipon*, promote and enhance agro-ecological-based farm coping practices, including creating a knowledge base of biodiversity, biological cycles and sound soil health and biological activities through their association. The government extension department only works for the use of saline or temperature-tolerant varieties and integrated resource management techniques as farmers' climate change adaptation program.

Both GO and NGOs offer a bundle of adaptation options for famers which can be divided into three basic features (described in table 4.7)

The farmers choose adaptation options according to their available resources and the nature of climate shocks that they face. The details of adaptation options chosen by sample farmers are presented according to the rice growing season.

Table 4.7 Alternative management practices for climate change adaption and low-carbon farming

Adaptation options	Adaptation benefit	Mitigation potential
Soil and crop management practice		
Integrated rice crop management	Low cost production technique by low resource use, minimum tillage, but labor intensive.	Normal water foodprint for rice is 2500-4000 liter/kg. Integrated rice crop management may reduce it by 25% and related CO_2 emissions may also be reduced.
Crop rotation with legumes	Ensures double benefit: sound soil heath and supplementary crop increase. In addition to this, reduces the application of chemical fertilizer, keeps moisture in dry weather and absorbs salinity from the soil.	Potential for low-level use of nitrogen fertilizer and fewer CH_4 (methane) emissions.
Use of saline tolerant variety	Sustainable tool for preventing climate change shocks.	No direct mitigation potential.
Best fertilizer management practice		
Use of balance fertilizer dose	Avoids the adverse effects of high temperatures and soil organic matters. Ensures good production.	Controls nitrogen emissions from rice farming.
Nitrogen deep placement	Proper use of nitrogen fertilizer lowers fertilizer costs and prevents shocks.	Correct place of nitrogen for easy access to crop roots controls methane emissions.
Irrigation water management		
Irrigation and rain water harvesting	Provides quality irrigation water by deepening well and rain water harvesting for instances of less rain and high temperature shocks.	Rain water harvesting provides a potential low carbon irrigation technique.
Water reservoir and diversion ditches	Ensures saline free water for *Boro* cultivation and washes out saline water by diversion ditches.	Diversion ditches support wetting and drying management, and help to reduce CH_4 emissions by removing extra water. Otherwise it may cause anaerobic fermentation of CH_4.

Source: Author's own farm survey.

(a) Adaptations in the Amon rice growing season

Amon is a rain-fed rice growing season in the study area of mid-July to mid-December. Traditionally, the study area has tidal floods twice a day which bring saline water of the sea through the nearest coastal rivers and canal. The rice farmers wait for heavy rain to wash the salinity out and drain through canal. Following this, they plant the seedlings, and the frequency of rain helps the crop to survive under the salinity. If the rain is erratic and less frequent, the total cropping system is exposed to salinity shocks and the reduced precipitation and high temperatures hamper crop growth. Farmers are autonomously adopting alternative production management to avoid climate variability shocks. Extension agencies guide them in solving the problem.

To get an insight into the alternative management practices and their impacts on farm production, the study recorded the farmers' opinions about what adaptation practices were most desirable and the reasons they chose it, and ranked them accordingly. There are five common adaptation option combinations found in the Amon season. Each option comprises of several sub-components. There are three sub-components in the options for soil and crop management: zero tillage-based integrated crop management, inclusion of trace tolerant varieties and relay cropping by use of legume crops. The option for best fertilizer management consists of two sub-components: nitrogen deep placement and balance fertilizer dose use. For the irrigation water management option there are also two sub-components: irrigation by reserving rain water or by deepening wells for saline-free water, and wetting and draining practices by diversion ditches. For ranking, the non-adaptation is scored as 0; and one or more sub-components from each adaptation option score as one; likewise at least one chosen sub-component from two adaptations assigned is scored as two. Similarly, from the three main adaptation options at least one sub-component chosen from each will score 3. The detailed descriptions are presented in the following sub-sections.

1. Soil and crop management with saline-tolerant seed varieties (Amon-1)

Farmers now have knowledge about natural uncertainty as they have been experiencing climate variability for several years. They are interested in having climate stress-tolerant varieties and using the seed to prevent climate shocks. Saline and stress-tolerant seed varieties of rice have been developed to defend against the effects of climate change. The extension agencies have successfully disseminated these promising varieties which maintain the yield even under extreme conditions of saline, drought or submergence (presented in the figure 4.3).

The sample farmers follow strategies in condition of few resources and quickly apply them to resilience threshold production. This adaptation tool is scored 1 out of 3 as an adaptive performance by the extension agencies and incumbent farmers. About 50 percent of the sample farmers adapt this practice for the *Amon* rice season under climate shocks (figure 4.6). However, the main constraint of this adaptation tool is that the seeds are not commercially available to the farmer. Sometimes they choose local varieties instead of HYV, and the yield performance is very poor.

Table 4.8 Some saline-tolerant varieties in Bangladesh

HYV varieties	Tolerance level	Local varieties	Tolerance level
BRRI -40	8-10 dS/m	*Shaheb Kochi*	5-6 dS/m
BRRI-41	8-10 dS/m	*Nona Kochi*	5-6 dS/m
BRRI-53	8-10 dS/m	Sada Mota	5-6 dS/m
BRRI-54	8-10 dS/m	Lal Mota	5-6 dS/m

Note: dS/m= desiSiemen per metre (a salinity measurement unit: 1dS =1000 EC = [Electrical Conductivity]
Source: DAE and expert opinion

2. *Soil and crop management through relay cropping with legume, and balanced fertilizer application (Amon-2)*

This is a technique that maintains soil health by introducing legume crops at the 4 weeks before the major crop rice harvest (presented in the figure 4.4). The legume relay crop has the power of fixing nitrogen in soil directly from the atmosphere (Ladha 1992). This traditional method helps to keep soil moisture for drought or precipitation shortages at the time of mature stage of the main crop harvest. It also ensures the double benefits to farm income by giving two outputs: the main rice output and the supplementary pulse crop white pea or local named Khesari (*Lathyrus sativus L.*). It keeps the soil fertile by providing required nitrogen with biological process (Ladha 1992).

The famers' opinions of the plant are that it can absorb salinity from the soil, but there has been no scientific background to this until now. The sample farmers combined this type of adaptation with balanced fertilizer application. They use three categories of fertilizer (nitrogen, potash and phosphate) in doses recommended by the DAE. The management technique ensures cautious use of nitrogen fertilizer for climate variability adaptation and mitigation. In Bangladesh farmers are not aware of balanced fertilizer use according to the needs of their land (Basak 2010).

They mostly use the nitrogen-based fertilizer urea as it is cheap and available. Other necessary fertilizers such as triple super phosphate (TSP) and mutate of potash (MP) are relatively expensive.

Figure 4.3 Planting stage of saline-tolerant rice variety in the field

Source: Author's own farm survey

Figure 4.4 Relay cropping in Amon rice field with Khesari (Lathyrus sativus L.)

Source: Author's own farm survey

In addition, the results of urea application through plant vegetative growth are visible. Farmers are interested to use only nitrogen based fertilizer, but they do not have balanced fertilizer use knowledge (Huda and Khan 2014). Excessive nitrogen adversely affects crops in condition of high temperatures and salinity. Also nitrogen directly emits into the atmosphere and creates methane gas that is another significant GHG from agriculture. Hence, this adaptation strategy of balancing fertilizer use has two benefits: helping crops grow under climate shocks and helping to reduce GHG emission.

3. *Soil and crop management through relay cropping with khesari (Lathyrus sativus L.) including balanced fertilizer application and irrigation management by diversion ditches (Amon-3)*

Approximately 13 percent of the sample farmers who adopted this production practice avoided the effects of climate shocks. This alternative management involves three major components: soil and crop management, fertilizer best management and water management by diversion ditches. This management practice is mostly the same as the preceding practice, but in addition, this practice involves a water management technique of diversion ditches that supports the washing out of saline water by rain and keeping water at a level that the crop requires. The diversion ditches help to drain out extra water and ensure soil moisture (shown in figure 4.5). When the fields are drained or permitted to dry at least once during the season the risk of high temperature shocks and fermentations may reduce the yield. The technique is also called alternative and wetting and drying AWD method (BRRI 2014).

It operates by checking water levels in soil and draining excessive water by diversion ditches. It ensures that 25 percent less water than usual is consumed. The technical background behind the technique is that when traditional rice fields are flooded with water, it cuts off oxygen supply from the atmosphere to the soil and results in anaerobic fermentation of soil organic matter. The methane emissions from the technique are much lower because, as ensured by the diversion ditches, there is no standing water in the growing season. 4 weeks before the rice harvest the relay crop *khesari* (white pea) is sown in the field. Hence, there are triple benefits: keeping the soil healthy, giving good production of rice and legume crops, and mitigating GHG emissions from the rice field. This adaptation tool is scored 3 out of 3 as an adaptive performance by the extension agencies and incumbent farmers.

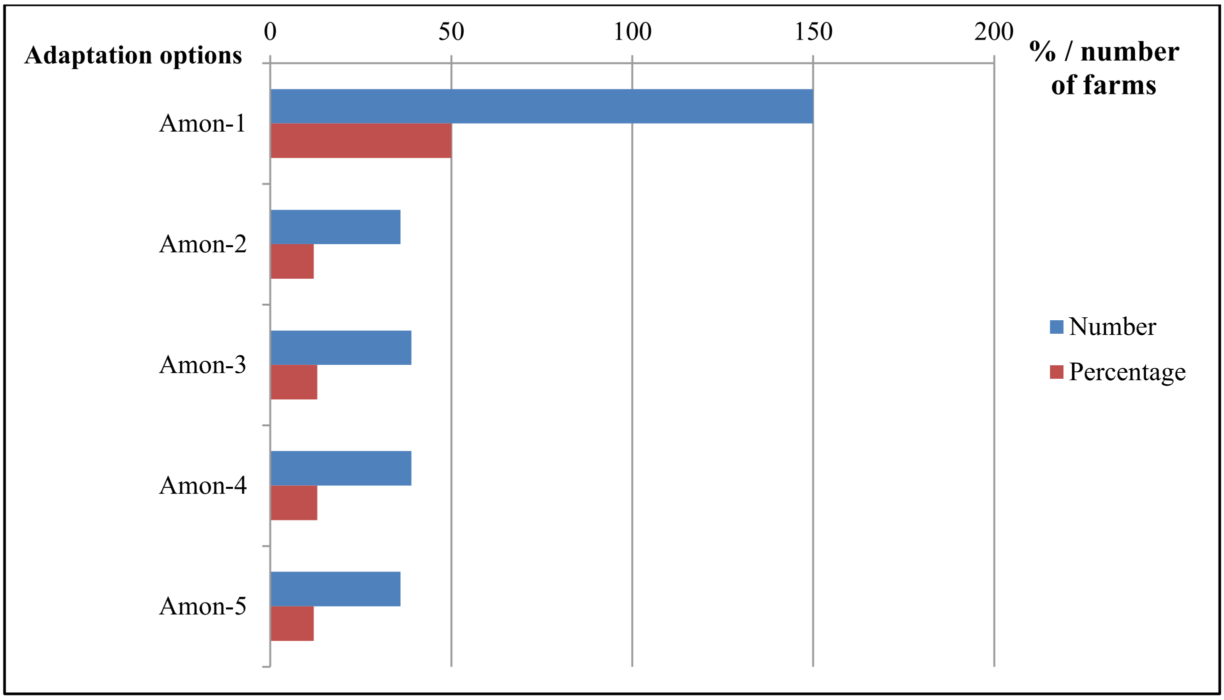
4. *Integrated pest management with saline-tolerant seed varieties (Amon-4)*

Under climate variability, one of the major challenges is the infestation of pests and diseases in crop fields. The frequency and severity increases in condition of high temperature and moisture. The technique described here is one of the best practices prescribed from last three decades for rice farmers in Bangladesh (FAO 2011). In areas prone to the effects of climate variability, the technology has become even more popular as an adaptation option for preventing climate shocks. The main motivation behind the management is avoiding chemical and commercial pesticides by introducing manual or tactical devices for pest infestations.

Figure 4.5 Amon season rice field management through balanced fertilizer application and irrigation management by diversion ditches

Source: Author's own farm survey

Figure 4.6 Adaptation options used in the Amon rice growing season



Source: Author's own farm survey

Typically, these include some beneficial and some non-beneficial pests or insects in the crop field. The Integrated Pest Management (IPM) recognizes both and prevents the pest or insect spreading from the probable sources by introducing traps and manual operations. This is knowledge-oriented management, and ensures an environmental and climate-friendly way of managing crops. The 13 percent of the sample farmers who adopt this option associated it with saline-tolerant seed varieties. It is scored only 1 because the option is environment-oriented and the productivity benefit may be very limited in quantitative forms; however, the option has merits for long-term soil health.

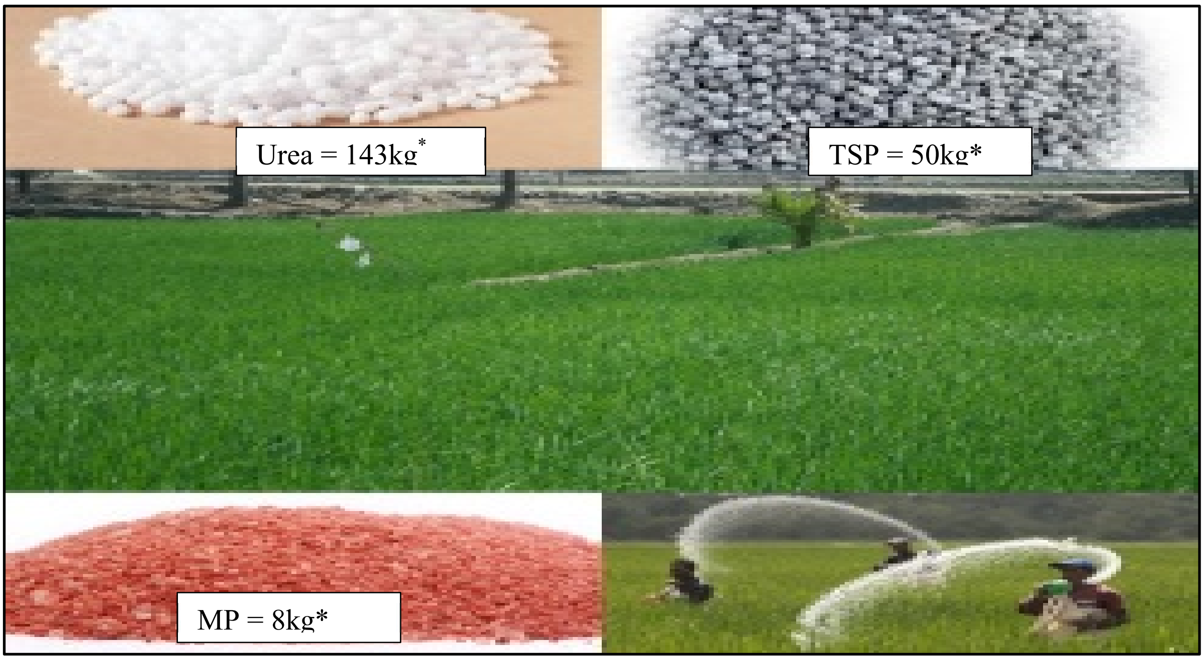
5. *Minimum or zero tillage-based integrated crop management with saline-tolerant varieties and best fertilizer management practice by nitrogen deep placement (Amon-5)*

The tillage disturbs and releases methane from the soil which is a cause of atmospheric emissions from rice cultivation. The disturbances from tillage create soil erosion and soil nutrition loss. Adopting zero tillage is not directly an adaptation option under climate variability, but rather a mitigation technique. However, in the case of climate shocks, farmers' main motivation is reducing cost of production by efficient use of resources, and optimizing the production by better use of technology. The final goal is bringing a farm net income to the threshold level. Zero or minimum tillage reducing tillage cost is an efficient way of maintaining soil nutrition in crop fields and it is a mitigation technique. The sample farmers practice the technique on flooded crop fields for 3 weeks and then paddle it for transplantations with minimum tillage.

They also applied it in association with saline-tolerant seed varieties and best fertilizer management practice by nitrogen deep placement. The nitrogen deep placement uses urea nitrogen fertilizer in granule form. The technique helps to use fertilizer on flooded rice fields efficiently, and at the same time prevents methane emission. The motivation is to make fertilizer more accessible to crop roots, and to slowdown or control the release of the nitrogen fertilizer.

In the study area the recommended dose for Amon is N (66)-P (10)-K (6). This means that, per hectare, the nitrogen requirement is 66kg, ensured by 143kg of urea; the phosphate requirement is 10kg, ensured by 50kg of TSP; and phosphorus requirement is 6kg, ensured by 8kg of MP per production period (BARC 2005). The example of best fertilizer management in *Amon* rice field is presented in the figure 4.7.

Figure 4.7 Amon rice field with integrated crop management and best fertilizer use options



* Amount per/ha for best fertilizer management practice in Amon rice of the study area (BARC 2005)
Source: Author's own farm survey.

(b) Adaptations in the Boro rice growing season

Boro is the biggest rice growing season in Bangladesh for area coverage and production. The season starts in January when transplanting begins, although seed sowing starts from mid-December, and the crop harvest is in mid-May. The modernization of *Boro* cultivation was initiated in the late 1960s. It used a production technology package including HYV seeds, supplementary nutrition by chemical fertilization, and the use of underground irrigation water. The HYV technology is a very sensitive production package, and any deficiencies may drastically reduce the yield. The study area has a successful history of producing rice in the *Boro* season. However, the expansion of shrimp culture as a result of the saline-water flooding through canals creates the problem of saline underground water. In addition the sustained rising of sea levels, the tidal flood around the crop fields severely affects the salinity level in underground water. According to statements of sample farmers saline-free underground water was available for up to 10 meters of depth in tube wells, but now, even deep tube wells no longer provide saline-free water. Recently it was reported that a tube well of 300 meters in depth could ensure saline-free irrigation water. Seasonal drought is also a problem in the *Boro* production system. Therefore farmers choose those techniques which ensure saline-free water to irrigate the field, and choose varieties of rice seeds that are that tolerant to temperature, drought and saline. There are about nine categories of adaptations found in the survey region (figure 4.8). These are based on irrigation water harvesting and drainage management.

1. Soil and crop management practice with climate stress-tolerant varieties including best fertilizer management as well as irrigation water harvesting (Boro-1)

This adaptation is an integrated approach that has three basic components of alternative management. These are climate stress-tolerant seed varieties from soil and crop management option; balance fertilizer use from best fertilizer management option; and irrigation water harvesting from irrigation management option (presented in figure 4.9). The sample famers use HYV stress-tolerant seed varieties invented by breeder agencies in Bangladesh (shown in table 4.9). The genetic enhancement of their local rice varieties promise higher yield potential and tolerance under adverse climate variability. There are several climate stress-tolerant rice varieties in Bangladesh (BRRI 2014).

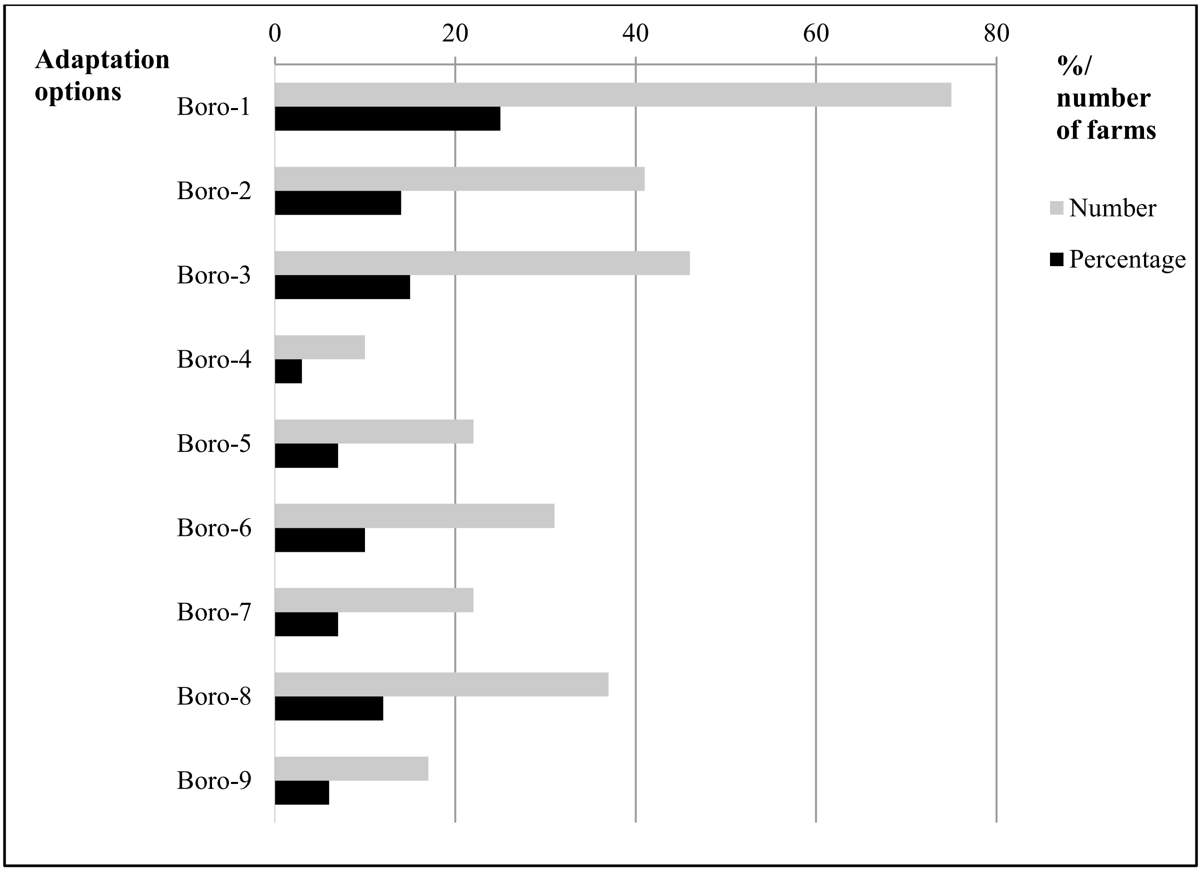
The other components are water harvesting by deep tube wells to ensure saline-free water, and use of balance fertilizer according to the fertilizer recommendation dose for the area.

However, this adaptation can only be afforded by the wealthier farmers in the study area because it requires investment, and the benefits come over an extended period of time. It is scored as 3 and 25 percent of the sample *Boro* rice grower adopted it.

2. Soil and crop management through saline-tolerant varieties and balanced fertilizer application by nitrogen deep placement with water harvest (Boro-2)

Under this adaptation technique three basic alternative production practices are applied to avoid climate shocks. The basic motivation is soil and crop management by maintaining soil health. The second element is balanced fertilizer application which means proper application of all necessary micro and macronutrients in a balanced proportion at different stages of crop growth (IFDC 2011). According to agri-ecological zone and soil characteristics, the adaptation aims at providing optimum plant development, maximum yield, ensures optimal profits and prevents damage to the environment. In the study area the recommended dose for *Boro* is N (80)-P(10)-K(27). This means that, per hectare, the nitrogen requirement is 80kg, ensured by 173kg of urea; the phosphate requirement is 10kg, ensured by 50kg of TSP; and phosphorus requirement is 27kg, ensured by 34kg of MP per production period.

Figure 4.8 Adaption options in *Boro* rice growing season



Source: Author’s own farm survey

Figure 4.9 Rice field with 3 basic adaptation option components for Boro season

Source: Author’s own farm survey

The efficiency of farmers' fertilizer nutrient budget is measured by the applied proportion as compared to balanced doses. The balanced fertilizer use is an adaptation as well as mitigation technique that controls the nitrogen and methane releases from the rice field. The nitrogen deep placement technique includes the placing of nitrogen more closely to crop roots as depicted in the figure 4.10. It improves nitrogen use efficiency, controls the release of nitrogen fertilizer and makes susceptible to losses, and it applies the right amount of fertilizer required for plants.

Figure 4.10 Nitrogen deep placement in Boro rice field including water harvest

Source: Author's survey

Figure 4.11 Boro rice field under irrigation management using diversion ditches

Source: Author's farm survey

An important component of the adaptation practice is ensuring supplementary irrigation arrangements by rain-water harvest. The study area is saline-prone and the underground water by shallow tube wells (STW) severely so. In the dry season, the degree of salinity increases, so farmers have to rely on harvesting rain-water or deepening the STW up to 300 meters to DTW. The second option is expensive and the farmers practice traditional irrigation pond excavation; the retention of rain-water in mini ponds of minimum 33 decimals in size at the corner to the land for supplement saline free water (see the figure 4.11). The practice scores a 3 for adaptation performance, but only 14 percent of the sample farmers could afford it.

3. *Crop management by saline-tolerant varieties, balanced fertilizer application with nitrogen deep placement as well as irrigation management by water reservoir and diversion ditches (Boro-3)*

This is an adaptation system that comprises three basic components of alternative farm management: soil crop management, best fertilizer management and irrigation water management. It scores a 3, and 15 percent of farmers apply it. The integrated crop and soil management uses saline tolerant varieties, balance fertilizer applications and efficient nitrogen management. Nitrogen based fertilizer urea is widely used in the study area, but under normal practice, it results in GHG emissions along with pollution in the ground water or high run-off. In order to improve the efficiency of fertilizer use, the farmers adapt urea deep placement, inserting granules deep in the soil.

The technique becomes a ‘food store’ for the plants ready to absorb when needed. The technique has mitigation potentials by reducing GHG release as well as adaptation merits that reduce urea use and increase production in adverse weather.

Farmers also design their field with near water reservoirs and diversion ditches to drain extra water. They keep the reservoir or mini pond at the middle surrounded by the rice fields. Reserve rain water is used two to three times for supplementary irrigation

The fields are also surrounded by earthen ridge to protect entry of saline water and diversion canals that helps to saline water exit as illustrated in the figure 4.11. The adaptation is labor and capital-intensive and requires maintenance every year.

4. *Minimum tillage-based integrated crop management with salt-tolerant varieties (Boro-4)*

This is a very simple adaptation option where the underground irrigation water is less saline or the susceptibility of saline water flow from canals is lower. The new rice varieties, BRRI-

47, BRRI- 55, and BINA- 8, are partly salt-tolerant varieties which can survive 8-10 ds/meter of salinity in underground irrigation water (see the table 4.9).

Table 4.9 Some climate stress tolerant HYV varieties in Bangladesh

Varieties	Yield/ha (kg)	Tolerance characteristics
BRRI Rice- 36	5400	Cold shocks-tolerant
BRRI Rice- 47	6600	Saline-tolerant
BRRI Rice- 55	6600	Drought, saline, and cold shocks-tolerant, short life cycle
BINA Rice- 8	5500	Up to 8-10 dS/m saline tolerant capacity

Source: Author's farm survey and Bangladesh Rice Research Institute BRRI (2014)

This component of adaptation gets a score of 1 by the farmers and only 3 percent of them adapt it. In fact, most of the places are now beyond the limits of tolerance from underground water.

5. *Best fertilizer management practice by balanced fertilizer, nitrogen deep placement including water reservoir and diversion ditches (Boro-5)*

This adaptation option comprises two basic components of adaptation without soil and crop management. 7 percent of *Boro* rice growers apply this technique and it scores 2 for adaptation performance by the respondent farmers. It only focuses on balancing and economizing nitrogen use in the field. A balanced fertilizer ensures sound production and nitrogen deep placement minimizes the production costs and methane emissions from the rice field as stated before.

As the *Boro* rice growing season depends on supplementary irrigation, the water reservoir provides the necessary saline-free irrigation water that is preserved from the rainy season. The success of the reserve system depends on the severity of seasonal drought in the summer. Furthermore, farmers adjust the production plan according to their size of the reservoir.

The extra water is drained by the diversion ditches which link back to the reservoir to repeat the process. The options also applied AWD method to check the actual requirement of water and manage it for economizing irrigation and prevent anaerobic fermentation of methane (presented the figure 4.12).

6. Irrigation water management with water reservoir and diversion ditches (Boro-6)

This adaptation tactic is applied to avoid climate variability shocks by harvesting and managing rain-water. Farmers use only one basic adaptation option and water management just ensures saline free supplementary water. It is practiced using the AWD method to check water requirements and economize irrigation water by management diversion ditches. Therefore, the practice has mitigation potential because it reduces the water and the carbon foot print in the production system. It is scored 1 as it uses only 1 adaptation option sub-component out of 3. About 10 percent of the sample *Boro* rice growers adopt it.

7. Soil and crop management practice with saline tolerant varieties associated with irrigation water management with water reservoir and diversion ditches (Boro-7)

This adaptation practice applies 2 basic components out of the 3, soil and water management, so the farmers scored it 3 for adaptive performance. The most common crop management applied here is alternative seed varieties that have the power to tolerate soil salinity.

In addition to this, irrigation water is managed by using a rain-water reservoir and a drainage system.

The diversion ditches are used to economize water use and aid to the effective feeding of nutrients. However, only 7 percent of the sample farmers can afford it. The adaptation is also capital-, and labor-intensive and only wealthy farmers are adopting it.

8. Zero tillage-based integrated crop management with saline tolerant varieties with water reservoir and diversion ditches (Boro-8)

This adaptation is a smart technique for preventing top soil erosion and reducing traction costs. In some places of the coastal area there is water stagnation up to mid-January. In these areas, farmers transplant the rice without any tillage, or minimum tillage as the stagnated rain-water leaves the land softer for transplantation. The farmers take the opportunity without the tillage, but they have to wait for late plantation after removing the possibility of stagnated water by surrounding canals.

They also use saline tolerant varieties because the risk of salinity comes earlier in the growing seasons. In addition to this they preserve rain-water in surrounding canals of the rice field and diversion ditches for irrigation management as presented in figure 4.15. The adaptation option was scored 2 for adaptation performance and only 12 percent of the sample farmers had adopted this technique.

Figure 4.12 Boro rice field under irrigation water management using AWD

Source: Author’s farm survey

Figure 4.13 Boro rice field irrigation by underground water harvest

Source: Author’s farm survey

Figure 4.14 Boro rice field using rain water from reservoir by manual water lifting device

Source: Author's farm survey

9. Best fertilizer management practice applied by balanced fertilizer (Boro-9)

The success of *Boro* rice production depends on the effective utilization of supplementary inputs such as irrigation and fertilizer. In fact, HYV rice production requires a specific production package with appropriate doses of fertilizer, seeds and irrigation. The best fertilizer management practice by balanced fertilizer refers to a blanket dose of fertilizer for a particular area (AEZ) based on crop requirements and soil fertility status (BARC 2005). The sample farmers practice their production by proportionate use of three basic fertilizers, urea, TSP and MP. Traditionally, farmers use urea without knowledge of balancing nutrient requirements. The sub-optimal use of urea causes CH_4 emissions and reduces yields. On the other hand, over-use of urea releases nitrous oxide and, in flooded fields, creates anaerobic fermentation of methane. The knowledge and application of a balanced fertilizer ensures optimal use of nutrients as well efficient management of inorganic chemical fertilizers under climate shocks. The farmers score 1out of 3 for this adaptation performance, and only 6 percent of the Boro rice growers apply it as a single component.

4.5 Intermediate conclusions

Climate change compels farmers to alternatives to traditional agriculture, and the seasonal cycle of temperature already shows an increasing trend. The rainfall patterns have changed and saline water intrusion increases daily in the coastal area of Bangladesh. Rice is going through alternative production techniques and faces combined climate variability shocks of heat, seasonal drought, erratic rainfall and salinity intrusion. Alternative production practices have two motivations: adaptation under bio-physical change due to climate variability and expected climate change, and a contribution to mitigation. The farmers are more interested in production goals associated with reviving production up to the threshold level. There are five distinct adaptations found for the *Amon* and nine for the *Boro* rice growing seasons in the study area. All the practices have versatile merits as sound agricultural methods. They are also based on the available resources of the farmers. Interestingly, the adaptation options that farmers were choosing, totally depend on management efficacy and within the reach of farmers' capability instead of cost consideration. They relate to traditional practices by the farmers with the help of consultation with extension workers and the support services of agricultural development authorities. The scientific community can explore new research agendas from farm-level adaptation options. The policy planner can set out the priorities of interventions regarding climate change and policy-making for agriculture.

5 Economic implications of climate change and adaptation options in rice farming

This section sets out the economic implications of farm-level climate change impacts and farmers' motivation toward adaptation. Economic rationality implies assessing the cost of climate change impacts, the cost-effectiveness of coping mechanisms, and the cost of GHG emission in farm activities. All of these effects are important for the successful adaptation of farms from an economic viewpoint. Only a few studies have been conducted to analyze farm-level performance focusing on the global climate change perspective. This study tries to identify merits of coping mechanisms among the available options using traditional farm management analytical tools and descriptive statistics. It is based on the survey of three hundred farms prone to the effects of climate change in Bangladesh. An effective way of reviving the farm income to the threshold level is to reduce the cost and increase productivity, widening the scope of agricultural adaptation. It is shown that a combination of several farming practices of crop management, fertilizer application, and rainwater harvesting and irrigation achieves three benefits. These are low-resource use to ensure productivity, earn high farm net income and at the same time reduce GHG in production, and farm operation under adaptation to changing climatic conditions. The results suggest that farmers' pathway to low-carbon farming under different adaptation practices may reverse the negative climate change impacts for future generations.

5.1 Introduction

Alternative agro-climate and eco-system services are new challenges for the farm economy. The community faces climate change and may change production practices and existing management. A coping mechanism that uses ecological, social, and economic systems in response to climate stimuli and their effects is defined as adaptation. More specifically, farm-level adaptation may refer to process, action, or outcome in a farming system for better adjustment to climatic stress, hazard, risk or opportunity (McCathy et al. 2011, Smit and Wandel 2006). An adaptation strategy may involve cost appreciation, cost reduction, input or output substitution and reduction in net earnings from threshold earnings. Farmers maximize their objectives in such a complexity of choices under uncertainty, risk, and volatility of investment benefit. These are the main economic implications of climate change and the impact of adaptation on farming.

The economic implications of climate change and adaptation at the farm level are not yet well understood. Farming is a risky business and impacts of climate variability cannot be easily separated from it. The slow and gradual effects of climate variability threaten the economic outcome of farming activities. It is essential that an assessment of climate change should comprise all its associated costs and benefits. When the cost of climate change and the net benefits of adaptation options are well understood, strategies and priorities can be defined for an effective combination of mitigation and adaptation measures for farming.

Nordhaus (1994) states adaptations could be realized up to a point where their marginal benefits equal to the marginal cost of adaptation. The straight-forward approach in economic valuation is to estimate costs of climate change impacts and to assess the costs and benefits of alternative adaption options. Valuation techniques can be based on: 1. directly observed market behavior, or 2. hypothetical market behavior (AGHGO 2004). The first approach addresses direct market pricing of costs and benefits and indirect market or surrogate market, pricing of cost and benefit of climate impact. The second category is applicable where value is not directly observable in the market. The common framework for costing the impact of climate change is given by welfare economic theory. It addresses the externalities, uncertainties, and equity with a monetary value of the impacts of climate change and provides methods and tools. Welfare economics typically applies partial equilibrium analysis and general equilibrium analysis. Partial equilibrium analysis assesses the impacts of climate change on a single sector, while general equilibrium analysis deals with economic effects through the whole economy.

Therefore, for an economic analysis of climate change impacts and adaptation options, impacts have to be identified first. The partial equilibrium analysis technique is appropriate for this. It can be applied in the context of local-scale climate change impacts and possible disaggregation sectors and sub-sectors. These bottom-up studies may assess impacts under the assumption that climate change impacts will not be large or indirect (AGHGO 2004).

5.2 Analytical framework and tools

Climate change impacts indicate the difference between conditions of a system with and without climate change (Ahmad and Warrick 2001, Adams et al. 1998). This analysis includes all the potential impacts of climate change from the direct bio-physical impacts to the indirect ecological and social ones. Climate change adaptation is the adjustment that helps to reduce the susceptibility of a community to the effects of climate change and can be both behavioral changes as well as technological adjustments. The aim is to cope with climate change with tactical as well as strategic adjustment (Frankhauser, Tol and Pearce 1997). The assessment of adaptation impacts includes the gross benefit of adaptation. This can be quantified by referring to the extra cost and extra benefits of the coping mechanism. By assessing the efficiency of resource use within different adaptation options and the mitigation potential, farm management decision-makers can decide which adaptation option offers the greatest benefits relative to threshold or non-adapted productivity.

5.2.1 Adaptation appraisal

(a) Farm performance analysis

Both commercial and subsistence farmers are suffering economic losses due to climate shocks. These losses can be measured as the increased resource inputs and the loss in the value of the output when referring to productivity (AGHGO 2004). Choosing the approach depends on the anticipated response of producers' impact. There are a number of tools and indicators available with which production cost, productivity or farm net income can be measured. These are:

Gross margin analysis: This method refers to the units of output and the estimated change in output due to climate change or adaptation impact.

Agricultural land assessment: This method estimates changes in land value with and without climate change and the impacts may indicate variability of productive capacity comparing the unit costs of resource inputs such as water requirements before and after changes and adaptation.

The total budgeting approach: It may help to estimate the difference between net incomes (the value of gross output minus gross resource inputs) with and without climate change or adapted or non-adapted conditions.

The partial budgeting approach: It can be used to estimate the marginal change of output or farm net income due to alternative production practices for adaptation to climate change. It is a tool to analyze change in farm business by input substitution, output substitution or technology adoption.

All methods are popular appraisal techniques for estimating the net benefit of adaptation to specific climate change impacts for the purpose of choosing between different adaptation alternatives. These estimates focus on the economic implications of climate change and adaptation options for optimizing farm goals at alternative bio-physical changes and ecosystem services.

The study uses most of the analytical tools described for appraising adaptation techniques and the impacts of climate change. On the basis of the estimated indicators, the impacts of climate change and adaptation options were compared with a base line (or reference) scenario to visualize the net effects.

Descriptive statistics of adaptation practice are presented for the two main rice growing seasons, *Boro* and *Amon*. To get an overall idea of impact and adaptation, this study used all the indicators. The analysis of impact of farm management strategies on per hectare productivity (yield, gross margin, net margin, and returns to land) uses the mean variance method (Just and Pope 1979). The variance of the productivity in a specific season indicates production risk. The comparison of mean productivity for threshold to non-adapted periods and non-adapted periods to adapted periods reveals the impact of climate change and adaptation efficacy.

(b) Cost-Benefit Analysis by benefit cost ratio (BCR)

The appraisal of adaptation options is also done using one of the CBA techniques: BCR. This is an economic decision support instrument that compares benefits of adaptation with the cost of the implementation of an adaptation option. Some adaptations have investment costs at the initial stage and resource maintenance costs each year in addition to production costs. For these investments, the undiscounted full costs are used in the BCR analysis to assess the financial performance of rice farming after adaptation.

(c) Cost-Effectiveness Analysis

This is an economic decision-support instrument widely used to determine least-cost pathways to advise on economic or environmental goals (AGHGO 2004). In the study, CEA provides the estimated benefits in kind (for example, quantity of rice) for adaptation options that are likely to be achieved for 100 BDT spent on adaptation as a given cost. For simplification, the assumption is to revive production up to the threshold level. In the first step, the method identifies the cost of each option. Then, the benefits as incremental outputs that are achieved by each alternative option are quantified. Finally, the cost-effectiveness of an adaptation option is calculated by determining the amount of BDT necessary to cover the rice production towards thresholds under climate shocks. This also indicates how much incremental rice could be produced for 100 BDT spent on an adaptation option.

5.2.2 Data sources

The study uses the data from the field survey and, thus, a total of 300 farm households prone to the effects of climate change. Part of the 13th agro-ecological zone that the study covers, where production is considered to have medium potential, is of tidal flood plains. The three sample coastal districts, *Khulna, Sathkhira* and *Bagherhat*, were purposely selected in consideration of the farm income vulnerabilities in the regions. Selection was also based on the existence of GO and NGO-supported projects for climate change adaptation and GHG mitigation. Three *Upazila* were purposely selected for the same attributes of representation.

Detailed cost and production information was collected for 2006 (provided by the farmers' records in association and memory). This period of production is considered the threshold level. There was no severe effect of climate variability on production in the area up to 2006. The next three years, 2007, 2008 and 2009, are considered the climate shocks period. After two devastation sea storms *Sidre* (2007) and A*ila* (2009) the production system, the farmers claim, underwent severe changes. This period is assumed as production without coping strategies under adverse climate variability or the non-adapted period for the sample farmers. From 2010 to 2013 the sample farmers adopted alternative production systems in their fields; this period is the adapted period. Farmers' bench mark data on different thresholds was recorded by the farmers when they joined the farmers' club. Hence, data of inputs and outputs were cross-checked with bench mark records kept by the farmers' club.

Detailed information on adaptation practice, production stages, labour endowment, land preparation, fertilizer use, irrigation efficiency and variety status was collected. Data was available for the years 2006 to 2013 that is 8 years of the respondent farmers' production status.

5.3 Results and discussion

5.3.1 Economic implications of the farmers' perception and climate change impacts

Most of the sample farmers perceive that changes in present climate compared to 20 years ago comprise less rainy days in the dry season, a delay of the rainy season, increased temperatures and more hot days associated with a higher-than-average maximum temperature. They consider 2006 as the last year with a stable climate. Following 2006, the basic climate parameters have not returned to the farmers' normal threshold ranges. After a devastating tropical sea storm named *Sidre* in 2007, there was significant rising of the sea level around the coast of Bay of Bengal. This created shocks such as salinity intrusion in rice fields and water stagnation. Traditionally, the areas of agricultural land have been marginally salinity-prone, but farmers could wash away the land and remove the problem of salinity with available rain-water. After sea levels, however, problems have increased: water stagnation has worsened on average, maximum temperatures risen, and there have been changes in the magnitude of the rainy season. The famers' production systems have faced a new bio-physical and ecological environment that was created by climate variability and the secondary effects of salinity. Interestingly, farmers' perceptions about climate variability are truly reflected in the levels of productivity and farm income. From 2007 rice production per hectare in the *Boro* and *Amon* seasons compared to threshold production drastically declined (Table 5.1). Farmers are using extra input, water and labor to reach the threshold levels of output or the combinations of inputs that cost the least to ensure productivity resilience. They are faced with continuing climate variability shocks and increasing food insecurities.

Table 5.1 Comparison of the farm performance in the threshold (2006) and non-adapted (2007-2009) periods relative to climate variability impacts

	***Boro* season**				***Amon* season**			
	Yield (Kg/ha)		**Gross margin (BDT/ha)**		**Yield (Kg/ha)**		**Gross margin (BDT/ha)**	
	Threshold period	**Non adapted period**	**Threshold period**	**Non-adapted period**	**Threshold period**	**Non-adapted period**	**Threshold period**	**Non-adapted period**
Mean	4,113	2,448	53,472	34,985	2,536	1,786	39,066	24,995
Mean difference	1,614.2970 t = 11.5300 (0.00)		1,8486.9100 t = 10.1773 (0.00)		750.4596 t = 31.1063 (0.00)		7,970.5850 t = 27.2055 (0.00)	
Standard deviation	2,514.86	363.13	32,693.21	5,083.84	901.07	569.502	11,722.12	7,973.03
Co-efficient of variation	28	119	28	119	48	54	48	54

Note: t = pair t test value; figures in parentheses indicates provability levels that ensured a high level of significance.
Source: Author's own calculations from survey

Another sea storm *Aila* hit the study area in May 2009 devastating the rice farming system. In the period of 2007 to 2009, the sample farm households faced severe vulnerability of farm income to climate variability. The variability of yields and of gross margins indicates the impact of climate variability after the threshold climate. Figure 5.1 represents the relative performance of farm management at the threshold and in the non-adapted period.

The gross returns of *Boro* rice per hectare were estimated at 53,472 BDT (approximately 535 Euro) under the threshold climate, while this was 39,066 BDT (approximately 400 Euro) for the *Amon* season. Compared to the threshold, the average gross margin per hectare for both seasons drastically fell in the non-adapted period. This has important implications for farm income and welfare under climate variability, and the significant mean difference in yield and gross margins indicates this impact.

5.3.2 Adaptive response to perceived climate variability and its economic implications

The surveyed farmers have adopted a variety of coping mechanisms in response to climate change shocks. In the aftermath of sea storm *Aila* an intensive rehabilitation program was initiated by GOs and NGOs in the study area. The perceived knowledge of climate change in non-adapted periods and the agricultural rehabilitation programs of different organizations have directed farmers towards adaptation. Their alternative production practices can be categorized in three distinct management approaches for both growing seasons: soil and crop management practices, best fertilizer management practice, and water management practice. Each of the adaptation categories consists of sub-practice options for environment friendly agricultural activities. There are five specific adaptations for rice cultivation in the Amon season and nine distinct categories of adaptation for rice cultivation in the *Boro* season practiced by the sample farmers details described in chapter 5. Most of the individual practices also indicate that low carbon farming practice was introduced with the climate change adaptation extension program in the study area. The adaptation options are chosen depending on the available resources, growing season, and regional salinity level. The sample farmers rank the adaptation performance according to the net output gain, problems in their application, availability of resources, cost-effectiveness, and sometimes on adaptation and mitigation potential. Interestingly, most of the farmers have great awareness about climate variability and change, because of media reports, GO and NGO campaigns, and extension programs in the study area.

In order to assess the impact of a new adaptation management practices on farm production, this study has described the available fourteen adaptation options in detail. The overall economic performance is discussed in the following sections.

5.3.3 Relative farm performance under different adaptation options

Farm earning performance

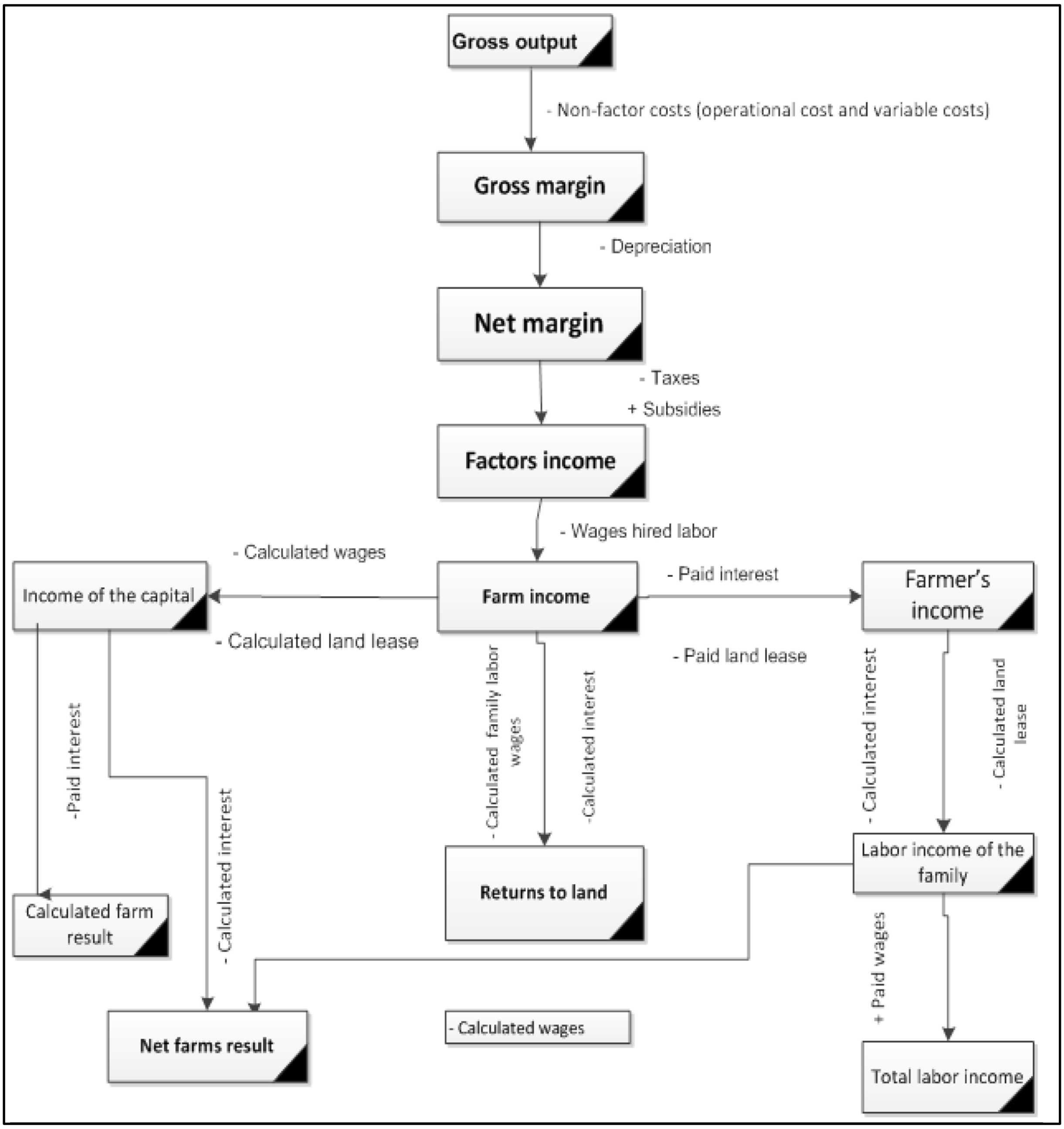
A budget approach estimates different performance indicators in farm management analysis. A farmer typically wishes to maximize his farm income subject to the exogenous conditions of the farm. The exogenous conditions are the farm's environment, including climate and ecology. Farmers choose a crop mix and inputs for each unit of land that maximizes the farm net profit.

A number of performance indicators is obtained from a complete budgeting approach according to figure 5.2. A key indicator is 'returns to land'. In this study, returns to land were estimated for threshold, non-adapted, and adapted periods. This is also the basis for Ricardian theory of land rent, and the basis for further analysis of the impacts of climate change on farms.

The 'returns to land' indicator effectively represents farm earnings and the impact on land under conditions of endogenous factor endowment for profit maximization subject to exogenous climate stimuli and adaptation dynamics. It is evident from table 5.2 that in returns to land all categories drastically decreased by weather variability in the non-adapted period. Adaption impact varies according to the nature of the practice and the seasons.

For the *Amon* season, almost all the adaptation options reap the benefits of reviving production, except option number 5 which tried to adapt only by saline-tolerant varieties with fertilizer deep placement. Adaptation option number 2, soil and crop management through relay cropping with *khesari (Lathyrus sativus L.)* and balanced fertilizer application, gives the greatest benefits among the *Amon* season options: farmers get double the crops in the same plot at the same time. Option 2 is followed by adaptation option number 3, soil and crop management through relay cropping with khesari (*Lathyrus sativus L*.) including balanced fertilizer application and irrigation management by diversion ditches considering the value of returns to land. Adaptation option 3 also provides double crop benefits as it helps to grow the legume crop in the same plot. Considering the threshold level of the returns to land value, it almost revives the full benefit of the threshold income. In the *Amon* season options number 1 and 4 moderately increase the value of returns to land but these are significantly lower than the threshold level.

Figure 5.1 Indicators of performance analysis for crop enterprise



Source: Adapted from Van Huylenbroeck and Calus (2008)

In the *Boro* season, seven out of nine categories of alternative adaptation options had positive impacts on the value of returns to land. Zero tillage with saline-tolerant varieties and best fertilizer management practice were found to not have a positive impact on returns to land. Although both options have merits in mitigation, the farmers claimed there is no positive economic impact. Water management in the *Boro* season is crucial for reviving the threshold level of productivity. Ensuring the water harvesting and diversion ditches, adaptation option 5 in the *Boro* season provides the highest returns to land among the available options. The second best option in the *Boro* season is adaptation option number 5 which only ensures irrigation water management with a water reservoir and diversion ditches. Considering the returns to land, the option 5 in the *Boro* rice growing season is followed by adaptation option 1 which uses soil and crop management practice with climate stress-tolerant seed varieties, including best fertilizer management practice, and irrigation water harvesting.

Table 5.2 Returns to land at different climate thresholds under adaptation options

Adaptations	**Returns to land (BDT/ha)**		
	Threshold period	Non-adapted period	Adapted period
***Amon* season**			
1. Soil and crop management with saline-tolerant seed varieties (*Amon-1*)	16,240	10,491	12,153
2. Soil and crop management through relay cropping with legume, and balanced fertilizer application (*Amon*-2)	38,485	27,903	32,685
3. Soil and crop management through relay cropping with khesari (Lathyrus sativus L.) including balanced fertilizer application and irrigation management by diversion ditches (*Amon*-3)	30,426	20,953	29,264
4. Integrated pest management with saline-tolerant seed varieties (*Amon*-4)	31,462	21,791	22,685
5. Minimum or zero tillage-based integrated crop management with saline-tolerant varieties and best fertilizer management practice by nitrogen deep placement (*Amon*-5)	14,290	9,519	7,518
***Boro* season**			
1. Soil and crop management practice with climate stress-tolerant varieties including best fertilizer management as well as irrigation water harvesting (*Boro*-1)	37,930	13,612	21,493
2. Soil and crop management through saline-tolerant varieties and balanced fertilizer application by nitrogen deep placement with water harvest (*Boro*-2)	31,534	14,588	16,738
3. Crop management by saline-tolerant varieties, balanced fertilizer application with nitrogen deep placement as well as irrigation management by water reservoir and diversion ditches (*Boro*-3)	26,975	11,697	13,934
4. Minimum tillage-based integrated crop management with salt-tolerant varieties (*Boro*-4)	35,164	14,281	16,105
5. Best fertilizer management practice by balanced fertilizer, nitrogen deep placement including water reservoir and diversion ditches (*Boro*-5)	40,912	17,787	29,350
6. Irrigation water management with water reservoir and diversion ditches (*Boro*-6)	33,850	16,919	26,427
7. Soil and crop management practice with saline tolerant varieties associated with irrigation water management with water reservoir and diversion ditches (*Boro*-7)	21,492	12,868	12,893
8. Zero tillage-based integrated crop management with saline tolerant varieties with water reservoir and diversion ditches (*Boro*-8)	31,490	16,162	16,005
9. Best fertilizer management practice applied by balanced fertilizer (*Boro*-9)	17,261	10,418	9,396

Source: Author's own farm survey

Interestingly, options 3 and 7 in the *Boro* season is used most of the available components, but the restoration performance was low. The reason behind this is the higher costs of inputs involved in implementing an integrated approach which reduces farm returns to land. At the same time, some regions salinity levels exceed the tolerance level in crop growing and, as a beginner, it will take time to fully adjust to the new practices.

Adaptation options 2 and 4 moderately increase the land value from the non-adapted period, but compared to the threshold level, the performance is low. Nevertheless, all adaptation options for the sample farmers have monetary as well mitigation merits. Compared to threshold levels, the returns to land indicator of the non-adapted periods significantly decreased. The hope is that the diminishing trends of such indicators for the sample farmer stops with successful coping mechanisms of the adaptation options.

5.3.4 Marginal impact of adaptation by partial budgeting approach

Partial budgeting evaluates the consequences of changes in farm methods which affect only part rather than the whole system of the farm (Dillon and Hardaker 1980). In the case of adaptation, farmers use a new technology package that affects performance.

Table 5.3 Marginal impacts of adaptation options using a partial budgeting approach in the Amon season

Options	Amon-1	Amon-2	Amon-3	Amon-4	Amon-5
A. Benefit forgone					
Gross margin forgone	33,408	39,144	41,129	41,784	39,144
New extra cost	18,945	23,011	18,846	20,531	18,668
Subtotal	52,353	62,155	59,975	62,315	57,812
B. Benefit gained					
Gross margin due to change	36,753	45,695	66,443	48,807	45,695
Cost no longer incurred	19,658	19,920	20,451	23,433	18,898
Subtotal	56,411	65,615	86,894	72,240	64,593
C. Net change = (B-A)	4,057	3,460	26,919	9,924	6,781

Source: Author's calculations based on the farm survey.

By comparing situations with and without the new alternative practices, the net effect on the whole farm performance can be estimated. This is also described as the marginal impact of change by production method substitutions. In the first step, the performance change as a result of adaptation is calculated based on the benefit forgone and the benefit gained. The benefit forgone has two sub-components: the gross margin forgone by introducing the new method (the gross margin without adaptation), and the extra cost for the new production practice. In other words, the benefit received under the present farm system would no longer be received for alternates systems (tables 5.3 and 5.4).

The benefit gained has two sub-elements: the gross margin due to change (that is, the gross margin after adaptation) and the cost no longer incurred for alternatives. Finally, the net change in farm profits associated with alternative adaptations can be calculated as benefits gained minus benefit forgone. If, after the calculation, the benefit gained is greater than the benefit forgone, the adaptation option is considered a feasible alternative. If the converse is true, the adaptation is not sustainable from an economic point of view.

Tables 5.3 represent the figures for adaptation options in the *Amon* season. The highest possible net change occurs with adaptation option 3 in the Amon season. Interestingly, if water management is absent in this adaptation option of the *Amon* season, the net gain drastically falls to the lowest level as indicated in case of option 2. Therefore, irrigation is an influential factor, which greatly affects the results, for this option. The soil and crop management practice only by saline-tolerant rice varieties marginally changes in gross margin. Farmers have potential for greater gain if they include integrated pest management to the varieties change. The marginal effect of adaptation option number 5 in the Amon season accounts for 6,781 BDT per hectare.

Table 5.4 Marginal impacts of adaptation options using a partial budgeting approach in Boro season

Options	**Boro-1**	**Boro-2**	**Boro-3**	**Boro-4**	**Boro-5**	**Boro-6**	**Boro-7**	**Boro-8**	**Boro-9**
A. Benefit forgone									
Gross margin forgone	45,893	38,865	40,096	41,258	39,310	34,820	41,357	39,534	35,781
New extra cost	27,063	26,942	28,252	26,867	32,974	32,167	25,267	25,417	36,943
Subtotal	72,956	65,807	68,348	68,125	72,284	66,987	66,624	64,951	72,724
B. Benefit gained									
Gross margin due to change	76,676	63,978	57,878	77,374	65,022	54,711	71,220	64,037	62,123
Cost no longer incurred	26,764	23,573	27,936	26,157	20,678	21,471	25,288	22,018	23,791
Subtotal	103,440	87,551	85,814	103,531	85,700	76,182	96,508	86,055	85,914
C. Net change = (B-A)	30,484	21,744	17,464	35,405	13,416	9,195	29,884	21,104	13,180

Source: Author’s own calculations based on the farm survey.

The five options assessed all have positive effects on the net change but the range is very high. Some options are reducing costs and some are increasing the gross margin. The farmers apply the practice according to their affordability and availability of resources. They claim their new adaptation knowledge is a first step to climate-resilient farming.

In the case of the *Boro* season, the highest possible net change occurs with adaptation option 4 because it is an option which notably reduces tillage cost and contributes to reducing production cost. If irrigation water is applied with the best fertilizer management as adaptation option 1 in the *Boro* season, cost increases, and the net gain decreases compared to option 4 under minimum tillage. Option 1 is the second best option in *Boro* season. Therefore, irrigation and fertilizer are influential factors in gross margin increase; however, the net change is less and cost is high compared to option number 4. Options 2, 3, and 8 provided moderate changes in net income after adaptation. Farmers have some potential for greater gain if they include soil and crop management with the saline-tolerant seed varieties. The marginal effect of adaptation option number 7 in the *Boro* season accounts for 29,884 BDT per hectare, which is the third best option in the *Boro* season. Adaptation options number 5 and 9 provided low changes in net income compared to the other available options. The marginal impacts of options 5 and 9 on net income change accounts for 13,416BDT and 13,180BDT per hectare of land respectively. Adaptation option 6 in the *Boro* season uses only irrigation water and diversion ditches which effects marginal changes in the gross margin.

The nine options assessed all have positive effects on the net change but the range is very wide. Some options reduce costs and some increase the gross margin to the same degree as that of the *Amon* season. The farmers apply the practice according to their affordability and availability of irrigation water resources. For long-term adaptation options they have to invest for an extended period of time and keep land resources for rain water reservoir which has opportunity costs. The financial analysis and economic appraisal can better present the implications of adaptation options as it accounts for such resources and the opportunity cost.

5.3.5 Appraisal of the adaptation options of the *Boro* and *Amon* rice growing seasons on the basis of the farm survey data

The farmers that are prone to the effects of the climate change have specific goals, including the resilience of farm productivity and returning revenue up to the threshold level. The goals relate to family food security and better livelihoods as a result of a stable farm income (Ramasamy 2012). According to the views expressed in the study survey, traditional and subsistence farmers are very rigid in their professional mobility even when vulnerability of income and opportunity costs is higher. They want to survive by changes within the farming system, and this makes adaptation options worthwhile. However, any adaptation or investment decision has to be economically assessed in view of available options. In the following CBA (using benefit cost ratio BCR indicator) and CEA are used for assessing the most valuable adaptation options in rice farming. BCR is one of the CBA tool indicating the financial performance of adaptations, while CEA indicates the total benefit for a given amount of money. Table 4.5 represents both the BCR and CEA of farm-level selected adaptation options. These analyses were considered only for the adaption options that need initial investment cost, pay-back periods and benefits come over an extended period of time.

Table 5.5 Cost-benefit and cost-effective analysis of adaptation options in Amon and Boro seasons

Adaptations	BCR	Cost-Effectiveness
1. Soil and crop management through relay cropping with khesari (Lathyrus sativus L.) including balanced fertilizer application and irrigation management by diversion ditches (*Amon*-3)	2.40	100 BDT spent on the adaptation ensures 10kg of rice
2. Soil and crop management practice with climate stress-tolerant varieties including best fertilizer management as well as irrigation water harvesting (*Boro*-1)	2.83	100 BDT spent on the adaptation ensures 8.04kg of rice
3. Soil and crop management through saline-tolerant varieties and balanced fertilizer application by nitrogen deep placement with water harvest (*Boro*-2)	2.37	100 BDT spent on the adaptation ensures 5.7kg of rice
4 Crop management by saline-tolerant varieties, balanced fertilizer application with nitrogen deep placement as well as irrigation management by water reservoir and diversion ditches (*Boro*-3)	2.05	100 BDT spent on the adaptation ensures 4.4kg of rice
5. Best fertilizer management practice by balanced fertilizer, nitrogen deep placement including water reservoir and diversion ditches (*Boro*-5)	1.9	100 BDT spent on the adaptation ensures 2.9kg of rice.
6. Irrigation water management with water reservoir and diversion ditches (*Boro*-6)	1.7	100 BDT spent on the adaptation ensures 2kg of rice
7. Soil and crop management practice with saline tolerant varieties associated with irrigation water management with water reservoir and diversion ditches (*Boro*-7)	2.82	100 BDT spent on the adaptation ensures 8.4kg of rice
8. Zero tillage-based integrated crop management with saline tolerant varieties with water reservoir and diversion ditches (*Boro*-8)	2.5	100 BDT spent on the adaptation ensures 5.9kg of rice

Source: Author's own calculations based on farm survey.

In the *Amon* season, adaptation option 3 is the only long-term investment option and has a BCR of greater than 2 which is quite impressive from a financial point of view. The value of BCR higher than one implies that the investment is feasible at given rate of interest as the benefits exceed the cost. The CEA for the same adaptation is also supportive because 100 BDT ensures 10 kilograms of rice, or the cost of 10 BDT/kg of rice. This adaptation option is feasible for its total benefit because the market price of rice is 15 BDT/kg.

In case of the *Boro* season adaptation option 1 this is also a feasible option as the BCR and CEA support application. *Boro* adaptation 2 is a financially sound adaptation practice and the CEA indicator also supports adopting the technology.

Boro season adaptation option number 3 is a feasible option in view of BCR and CEA indicators, whereas option number 5 is not financially viable providing only 2.9 kilograms of rice for each 100 BDT spent. Similarly, *Boro* season adaptation option 6 is not feasible because this adaptation provides only 2 kilograms of rice for each 100 BDT spent while the market value of two kilograms of rice is only 30 BDT.

Adaptation option 7 for the *Boro* season usually covers it cost. Finally, adaptation option 8 is also a feasible according to both indicators.

The alternative production system appraisal helps to set priorities for climate adaptation on farms. The overall assessment suggests that a single sub-component of an adaptation practice alone will not be enough for facing climate change. An integrated approach consisting of all system components, soil and crop management, fertilizer management, and irrigation option management, will be a feasible adaptation strategy.

5.4 Intermediate conclusions

This chapter presented the economic implications of adaption options in different ways. The assessment indicators of climate change adaptation were analyzed to find the performance of farms at different thresholds. There is not a single criterion to assess economic implications of climate change adaptation as the bio-physical environment and markets determine profitability and viability of farming. The profitability and success of farming depends on many exogenous and endogenous variables. Consequently, the analysis of the economic impacts of climate change adaptation options is challenging because the contributions of influencing factors are difficult to single out. Keeping in mind all the limitations, this study estimated the relevant indicators of farm performance using common economic tools. The basic findings of the study postulate that climate variability has a significant impact on rice production in both growing seasons. The effects are estimated in monetary terms. Results show clear farm income vulnerability from the threshold level due to climate change. As a consequence, farmers operated their farms despite climate shocks for some period and then adopted some alternative practices to build resilience in farm productivity and returns to the threshold level. These adaptations ensured benefits compared to the non-adapted period, minimized the costs of production and economized resource use. Some have mitigation potential and climate smart production merits for sound cultivation. There were 14 common practices found in the farm survey whose economic implications were assessed. Three basic components of adaptation were found to be important for full economic recovery: soil and crop management, nutrition application management and water management. The combined application of the three components can successfully revive the threshold productivity in the study area.

6 Economic impacts of climate change and adaptation options on farm net income: a bio-economic analysis

This chapter presents an empirical analysis of the impacts of climate change and adaptation options on rice crop farming in the coastal areas of Bangladesh. The economic implication of climate change and the related coping strategies are estimated by using a farm net income assessment with an advanced Ricardian approach. Repeated cross-sectional observations of 300 climate prone farms over 8 years were used for the panel analysis. The analytical framework is still rare in farm-level impact analysis. A specified fixed-effect farm revenue model was used to estimate the effect of climate variability, mainly that of the average maximum temperatures and average precipitation. Two separate empirical log-linear farm revenue models were specified and estimated based on the two rice growing seasons, *Boro* and *Amon*. Overall, the climate variability factors and further non-climatic factors were found to be significant determinants of farm net income in both seasons. The marginal impact of temperature on farm income was found to be negative and statistically significant for the *Amon* season, whereas it was negative and statistically insignificant for the *Boro* season. The marginal impact of rainfall was positive and highly significant for both models. It is evident from the analysis that successive adaptation significantly increases farm productivity and contributes to a revival of farm net income to the threshold level. Based on the estimated climate variability models of farm net income, the study simulated the function according to IPCC scenario predictions to forecast the adverse effects of climate change on future farm revenue.

6.1 Introduction

The Third IPCC Assessment Report (TAR) first projected the association of the impact of climate change with that of crop yield loss. This is mainly due to heat shocks, salinity in irrigation water, and the moister as a result of heavy precipitation in South Asian coastal areas (IPCC 2005). There is greater confidence in the Fourth Assessment Report (AR4) than in the TAR that projected patterns of adverse climate change have impacts on crop yield. The adaptive capacity is perceived to be low in developing countries, and higher temperatures and changes in precipitation have already increased the susceptibility of crops to damage in many countries (IPCC 2014, IPCC 2007a). The assessment of the economic impacts of climate change on agriculture directs towards proper adaptation strategies (Sachs, Panatayou and Peterson 1999).

Basak, Titumir and Dey (2013) found a trend of increasing temperatures in Bangladesh from 1976 to 2008. In the same period, precipitation changed: there is a trend of increasing Monsoon and post-Monsoon seasons, and a trend that shows a decreasing winter season.

Keeping in mind this development, some pertinent questions arise about the relationship of climate variability and the change in farm net income: What is the climate variability and adaption options impact on farm net income? Will coastal rice farming in Bangladesh be profitable in future climate change scenarios and dynamic adaptation?

For the evaluation of the impacts of climate change, as well as adaptation on agriculture, a hedonic approach (Ricardian approach) is widely used. For farm-level climate change impact analysis, Mendelsohn (1994) introduced the proper economic framework of Ricardian approach.

This framework takes into account economic considerations and human capital limitations which affect farm decisions. The Ricardian approach focuses on the long-term productivity of land reflecting an asset value. The logic behind the impact assessment technique is that any influence of climate variability and adaptation options will be reflected in farm net income and subsequently in land value. Applying econometric modeling to the impacts of different factors on land value or farm net income can be estimated by cross-sectional data. From the estimated model of the impacts of climate variability on farm net income, the future impact of climate change on farm land productivity can be determined.

The Ricardian approach implicitly incorporates adaptive behavior because a coping mechanism is an endogenous decision governed by various factors that may or may not be observable (Di Falco et al. 2012). There is the possibility of unobservable heterogeneity when we estimate via the Ricardian cross-sectional analysis. The problem of endogeneity of adaptation decisions and unobserved quality differences in farming is called the heterogeneity in this case; this problem may cause biased estimates and misleading inference (Deschenes and Greenstone 2007). Another short-coming of conducting farm-level climate change analysis with cross-sectional data is the lack of enough spatial variation of key climatic parameters, like temperature and precipitation (Di Falco et al. 2011).

To overcome the problem, panel data is applied in the case of US agriculture (Deschenes and Greenstone 2007). The economic impact of climate change on agricultural land is estimated by year to year effect of variation of temperature and precipitation on agricultural profit. According to Deschenes and Greenstone (2007), the inter-temporal method will eliminate cross-sectional variation and focus on year to year changes in weather. Their findings contradict the popular view that climate change has a substantial negative welfare consequence for US agriculture.

Mendelsohn and Massetti (2010) advance the Ricardian analysis of the impacts of climate change on agriculture by introducing panel data to the Ricardian method. Their panel method uses two different econometric models: the Hsiao model and the pooled regression model, which effectively controlled unobserved heterogeneity.

6.2 Data and estimation procedure

The study is based on the farm survey conducted on 300 farms of the south-western coastal area of Bangladesh near the Bay of Bengal. The data set comprises information of adaptation practice, production stages, labour endowment, land preparation, fertilizer use, and irrigation efficiency and crop variety used from 2006 to 2013.

Data for monthly rainfall and temperature was collected from three sources: the nearest meteorological stations (*Mongla and Sathkhira*) and the records of the nearest *Upazila* Agricultural Office were two sources of weather variability information for specific growing seasons over the investigated period. The third source of rainfall and temperature data for the study area was the Bangladesh Agricultural Research Council (BARC) website. In addition, information on soil characteristics, the scientific background of local climate shocks, crop diseases and salinity was collected from different published and unpublished sources of the local agricultural office and NGOs.

The traditional Ricardian model is estimated using a single cross section model as follows:

$$R_i = \beta X_i + \gamma C_i + \xi_i \tag{6.1}$$

where R_i is the value of land per hectare of farm i; X_i represents the socio-economic and farm-level characteristics; C_i stands for weather and climate variables; β and γ are the respective vectors of unknown estimates to be estimated; and ξ_i represents the error terms. The relationship between climate variables and land variables is assumed to be quadratic in the traditional Ricardian model. This implies that the climate variables include squared terms, and the effect of climate on land value varies across seasons (Mendelsohn, Nordhaus and Shaw 1994).

Using the panel data the Ricardian model can be estimated by repeated independent cross-sections (Mendelsohn, Nordhaus and Shaw 1994, Mendelsohn, Dinar, and Sanghi 2001, Schlenker, Hanemann and Fisher 2006, Deschenes and Greenstone 2007 and Massetti and Mendelsohn 2010)

When the model uses panel data allowing to control for omitted variables (unobserved or mis-measured) (Greene 2008), an ideal estimated model would have the following form: (Massetti and Mendelsohn 2012)

$$R_{i,t} = \beta X'_{i,t} + \gamma C'_i + \phi Z'_i + \xi_{i,t} \quad (6.2)$$

$R_{it}$is returns to land at time t of farm i; the socio-economic and farm-level characteristics variables are presented in two forms: $X'_{i,t}$ represents time-variant variables and Z'_i represents time-invariant control variables; β, γ, and ϕ are the respective vectors of unknown estimates to be estimated and $\xi_{i,t}$ as before represents the error terms but it is a composite error term now .

The advanced Ricardian model is estimated in two ways. One probable way is pooling the entire data and directly estimating the co-efficients using equation 6.2. The other way is the Hsiao two stages approach where in the first stage returns to land is regressed on the time varying variables using the covariance method by individual fixed effects (Hsiao 2008) as presented in the following:

$$R_{i,t} = \beta X'_{i,t} + \alpha_i \epsilon + \mu_{i,t} \quad (6.3)$$

where ϵ is a vector of individual specific fixed-effects (dummies), and $\mu_{i,t}$ are resulting error terms.

In the second stage, the time-mean residuals are regressed on the time-invariant variables as follows:

$$\bar{R}_i - \bar{X}'_i \hat{\beta}_{cv} = \alpha_i \epsilon + \bar{\mu}_i = \phi Z'_i + \gamma C'_i + \bar{\xi}_i \quad (6.4)$$

For both panel models we have to test whether the climate co-efficients are stable over time by estimating variant models. This testing technique allows the climate co-efficients to change; therefore, in the second stage of the Hsiao model, they estimate a separate set of co-efficients, γ_t by transforming the equation 6.4 as follows:

$$\bar{R}_i - \bar{X}_i'\hat{\beta}_{cv} = \phi\, Z_i' + \gamma_t C'_i + \bar{\xi}_{i,t} \tag{6.5}$$

This is equivalent to creating a set of time dummies for each year, and allowing for interaction between these time dummies with the climate variables.

In the case of the pooled model, this allows for interaction between the climate variables with year dummies as follows:

$$R_{i,t} = \beta X_{i,t}' + \gamma_t\, C_i' + \phi\, Z_i' + \xi_{i,t} \tag{6.6}$$

This model also yields a set of time-specific co-efficients for climate variables allowing to test whether co-efficients are stable over time.

When the same individuals (or entities) are observed for each period, the panel data set is called a fixed-panel. The fixed-effects model can be estimated as follows:

$$R_{i,t} = \delta_i + \beta X_{i,t}' + \gamma\, C_{i,t}' + \xi_{i,t} \tag{6.7}$$

where $R_{i,t}$ is per hectare returns to land at time t of farm i; $X_{i,t}'$ represents the socio-economic and farm-level characteristics over the period t; and $C_{i,t}'$ stands for climate variables over the t period. The fixed-effect model includes a full set of county (group) fixed-effect (individual specific effects) by using δ_i. The logic behind the inclusion of county fixed-effects is that they absorb all unobserved county-specific time-invariant determinants of the dependent variables (Deschenes and Greenstone 2007). β and γ are the respective vectors of unknown estimates to be estimated, and $\xi_{i,t}$ represents the error terms. By using the fixed-effect model the estimation allows for temporal variation replacing the climate variables with growing season climate variables C.

To estimate the impacts of climate change and adaptation options, equation 6.7 was used. For comparison it can be said that the approach suggested by Massetti and Mendelsohn (2012) was applied, but with little difference in the form and specification of the variables. The dependent variable, R, is individual farm-specific returns to land (a profit indicator), instead of land value. Since climate variability and change may affect farm net income and expenditure, these will result in damages to farm profit. Instead of assuming a quadratic relationship between the dependent variable and climate change parameters, a linear relationship was postulated. Furthermore, the model was formulated for the two growing seasons *Boro* and Amon for the whole years. The temperature as a climate variable is considered as the average maximum value. Semi-log or log-linear empirical models were fitted for the different approaches. To test the functional relationship, a Box-Cox test was performed.

6.3 Results and discussion

6.3.1 Estimation results

Table 6.1 represents the estimates of the empirical analysis describing the impacts of the climate variability and adaptation options on farm returns to land**.** For both rice growing seasons, the farm profit indicator returns to land depends on climate factors (maximum temperature and precipitation), adaptation (score of three broad adaptation options chosen: soil and crop management, best fertilizer management practice and irrigation water harvesting and management) and some farm specific socio-economic variables (age of farm owner, access to irrigation for *Boro* model only, variety dummy, production cost and ratio of fertilizer budget to balance dose). The estimates for climatic variables are statistically significant for both the *Boro* and *Amon* model specification with log-linear form and fixed-effect equation.

The scores of the adaptation options provide strong significant evidence that the adaptation strategies undertaken by farmers are correlated with farm profit and responsiveness to climate shocks. Among the farm-specific socio-economic variables, the age of the farmer is negative and strongly significant for both growing season models. Access to irrigation for the *Boro* season model seems to play a very important role and it correlated positively to returns to land. This implies that farmers who have quality irrigation earn higher returns to land than those who do not.

For the *Amon* season, with a fully rain-fed production practice, the access to irrigation is not applicable. Interestingly, the variety dummy is positive and statistically significant for the *Boro* season, yet for the *Amon* season it was found to be statistically insignificant and positive. The logic behind the significance in the *Boro* season and insignificance in the *Amon* season for the same dummy is that the *Boro* production system applies is a high-yielding package including fertilizer and seed, whereas the *Amon* production system is based on rain-fed technology on local indigenous varieties.

Table 6.1 Variables explaining the impacts of climate variability and adaptation options on returns to land using a fixed-effect model

Variables	Boro Season[1]	Amon season[2]
Returns to land per hectare (dependant variable)		
Climate/Weather factors		
Temperature Boro season	-0.041*	-
Temperature Amon Season	-	-0.176***
Precipitation Boro season	0.003***	
Precipitation Amon season	-	0.0056***
Adaptation		
Adaptation option rank (1 to 3)	0.1758172***	0.1941283***
Socio-economic factors		
Age of owner	-0.0793326***	-0.0815643***
Access to irrigation dummy (0/1)	0.3126119***	-
Variety dummy (0/1)	0.1569749***	0.0391832
Ratio of fertilizer budget to balance dose	0.0024102***	0.0000865
Production cost	-0.0000874***	-0.0000936***
Constant	15.65833***	18.28995***
Goodness of fit indicators		
R^2 Within Between Overall	 0.4549 0.0517 0.0968	 0.5747 0.0136 0.0011
F-value (dependable variables, no. of observations-Panels-dv)	229.94 (8, 2091)	403.83 (7, 2092)
Corr. (u_i, Xb) Prob > F	-0.8208 (0.000)	-0.8096 (0.000)
sigma_u sigma_e	0.94614372 0.38016721	1.24973 0.297358
rho (fraction of variance due to u_i)	0.86099354	0.946419
F test that all u_i=0: F(panels-1, observations-no. of panels-no. of variables) Prob > F =0.0000)	7.31(299, 2091) (0.000)	24.10 (299, 2092) (0.000)

***Significant at 1 percent level, ** Significant at 5 percent level, *Significant at 10 percent level

1. Based on appendix table 2a. 2. Based on appendix table 3a

Source: Authors own estimates based on survey the data

However, the *Boro* season high-yielding varieties significantly increase returns to land, but in the *Amon* case the varieties are not a significant factor. The ratio of fertilizer budget to balance doses positively impacts on returns to land for both seasons, but in the case of the *Amon* season, the estimated co-efficient is not significant. Lastly, production costs of farming negatively impact on returns to land and were found to be significant for both models.

6.3.2 Analysis of marginal impacts of climate variability and adaptation score on returns to land per hectare of rice production in different seasons

From the estimated coefficients of equation 6.7 marginal impacts of climate variables can be observed. In the same way, marginal impacts of adaptation scores can be calculated. Table 6.2 shows these marginal impacts of climate variability and adaptation score on rice farm returns to land based on the empirical models. According to the log-linear model results, an average *Boro* season maximum temperature increase by 1 degree Celsius results in a decrease in returns to land per hectare by 4.1 percent from its threshold level for all farms in the sample.

For the *Amon* model the marginal impact of the average maximum temperature was found to be higher. *Amon* season returns to land will decline from the threshold level by 17 percent for an increase in the average maximum temperature of 1degree Celsius.

Table 6.2 Scoring of the marginal impacts of climate variability and adaptation score on rice farming returns to land per hectare

Season	Marginal impact			Standard error SE
Boro	Average maximum temperature	Υ_{tem}	-0.041^{*}	0.0253175
	Average maximum precipitation	Υ_{pres}	0.003^{***}	0.0012633
	Adaptation score	β_{ad}	0.1778^{***}	0.0153079
Amon	Average maximum temperature	Υ_{tem}	-0.1758^{***}	0.0259142
	Average maximum precipitation	Υ_{pres}	0.005^{***}	0.0003383
	Adaptation score	β_{ad}	0.1941^{***}	0.0140767

***Significant at 1 per cent , ** Significant at 5 per cent, *Significant at 10 per cent
Source: Author's own estimates based on the survey data

Conversely, for an average precipitation increase of 100 mm, returns to land will increase by 3 percent for the *Boro* season and 5 percents for the *Amon* season. The *Amon* season is comparatively more vulnerable to the impact of climate variability.

Therefore, when farmers adopt coping mechanisms with climate change, the marginal impact of the adaptive strategies may be higher. In fact, the marginal impact of adaptation as measured by the adaptive score in the empirical model is 17.8 percent of returns to land which can be achieved by succeeding with one unit score increase of adaptation performance in the *Boro* season. In the *Amon* season this is accounted 19.4 percent additional average returns to land. The results of the analyses of marginal impacts of climate variability and adaptation options suggest that proper coping mechanisms and adaptation strategies substantially protect farmers from losses from climate shocks.

6.3.3 Effects of future climate change

This section addresses the potential impacts of specific global climate change scenarios to rice farming in the southwest coastal region of Bangladesh.

Table 6.3 Future global climate model scenario for Asia

Year/Season	Mean temperature change (°C)		Precipitation change (%)	
	A1FI (highest future emission trajectory)	B1 (lowest future emission trajectory)	A1FI (highest future emission trajectory)	B1 (lowest future emission trajectory)
2010-2039	0.95	0.89	2.50	5.50
DJF	1.17	1.11	-3.00	4.00
MAM	1.18	1.07	7.00	8.00
JJA	0.54	0.55	5.00	7.00
SON	0.78	0.83	1.00	3.00
Boro (JFMAM)	1.18	1.09	2.00	6.00
Amon (JASOND)	0.66	0.69	3.00	5.00
2040-2059	2.56	1.54	11.75	10.25
DJF	3.16	1.97	0.00	0.00
MAM	2.97	1.81	26.00	24.00
JJA	1.71	0.88	13.00	11.00
SON	2.41	1.49	8.00	6.00
Boro (JFMAM)	3.07	1.89	13.00	12.00
Amon (JASOND)	2.06	1.19	10.50	8.50

Note: The seasons are indicated by the name of the months; that is DJF = (Dec., Jan., Feb.); MAM = (Mar., Apr., May); JJA = (Jun., Jul., Aug.); SON = (Sept., Oct., Nov.); JFMAM = (Jan., Feb., Mar., Apr., May); and JASOND = (Jul., Aug., Sept., Oct., Nov., Dec.).

Source: Adapted from Cruz et al. (2007)

The scenarios are based on the Fourth Assessment Report (AR4) and Atmospheric-Ocean General Circulation Models (AOGCMs) of sub-regions of Asia under Special Report on Emissions Scenarios (SRES) of IPCC. They assigned the scenario as A1F1 and B1 which will represent different emission paths and climate change. On SRES, A1F1 implies the highest future emission trajectory whereas B1 indicates the lowest future trajectory for three time periods: 2020, 2030 and 2080.

This study used the temperature and precipitation forecast up to the year 2060. It was found in the models that the temperature rise for this area will vary from 0.54°C to 1.18°C by 2040 and from 0.88°C to 3.16°C by 2060 (Table 6.3).

In the case of precipitation, the range varies from –3 to +8 percent of change for the first time period up to 2040. For the next period up to 2060, calculations indicate a range of precipitation increase from 0 to 26 percent. The following climate change predictions have been used for scenario calculations for the *Boro* and *Amon* seasons.

Table 6.4 Climate change predictions for future climate scenarios

Year /Season	A1FI (highest future emission trajectory)			B1 (lowest future emission trajectory)		
	Temperature change	Precipitation change	RTL (BDT/ha)	Temperature change	Precipitation change	RTL (BDT/ha)
2010-2039						
Boro (JFMAM)	1.18	2.0	6,393	1.09	6.0	6,362
Amon (JASOND)	0.66	3.0	1,649	0.69	5.0	1,696
2040-2059						
Boro (JFMAM)	3.07	13.0	6,259	1.89	12.0	6,274
Amon (JASOND)	2.06	10.5	1,285	1.19	8.5	1,480

Source: Adapted from Cruz et al. (2007) and estimation from the panel model of the study.

(a) Effect of future climate change on Boro returns to land

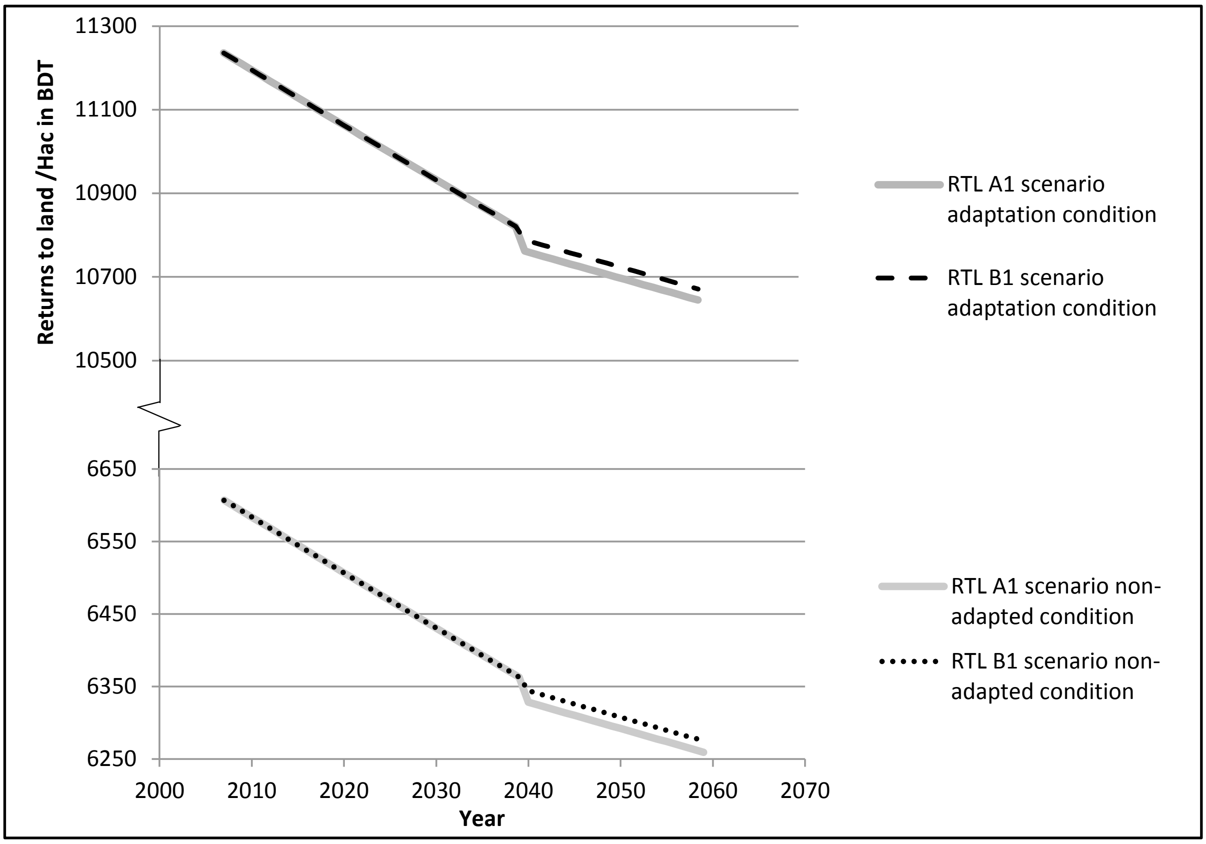
For the *Boro* season, the temperature rise will be between 1.09°C and 1.18°C for the first time period and it will rise between 1.89°C and 3.07°C in the next time period.

For the *Amon* season, the temperature will moderately rise and will be similar for the highest and lowest emission trajectory in the first time period. In the period up to 2060 the *Amon* seasonal temperature rise will be in the range of 1.09°C to 2.06°C. Precipitation of the region will gradually rise in both rice growing seasons.

Figure 6.1 illustrates the development of the returns to land according to the estimates of panel regression for the *Boro* growing season both for the highest future emission trajectory (A1F1) and the lowest future emission trajectory (B1).

The climate change scenario for future temperature and precipitation increases under A1F1 and B1 and will lead to a negative trend in returns to land in the *Boro* season until 2059. Interestingly, figure 6.1 indicates that this will be for both adapted and non-adapted conditions, but the adapted farmers will have higher returns to land over time.

Figure 6.1 Simulated returns to land of the Boro rice growing season in future climate scenarios



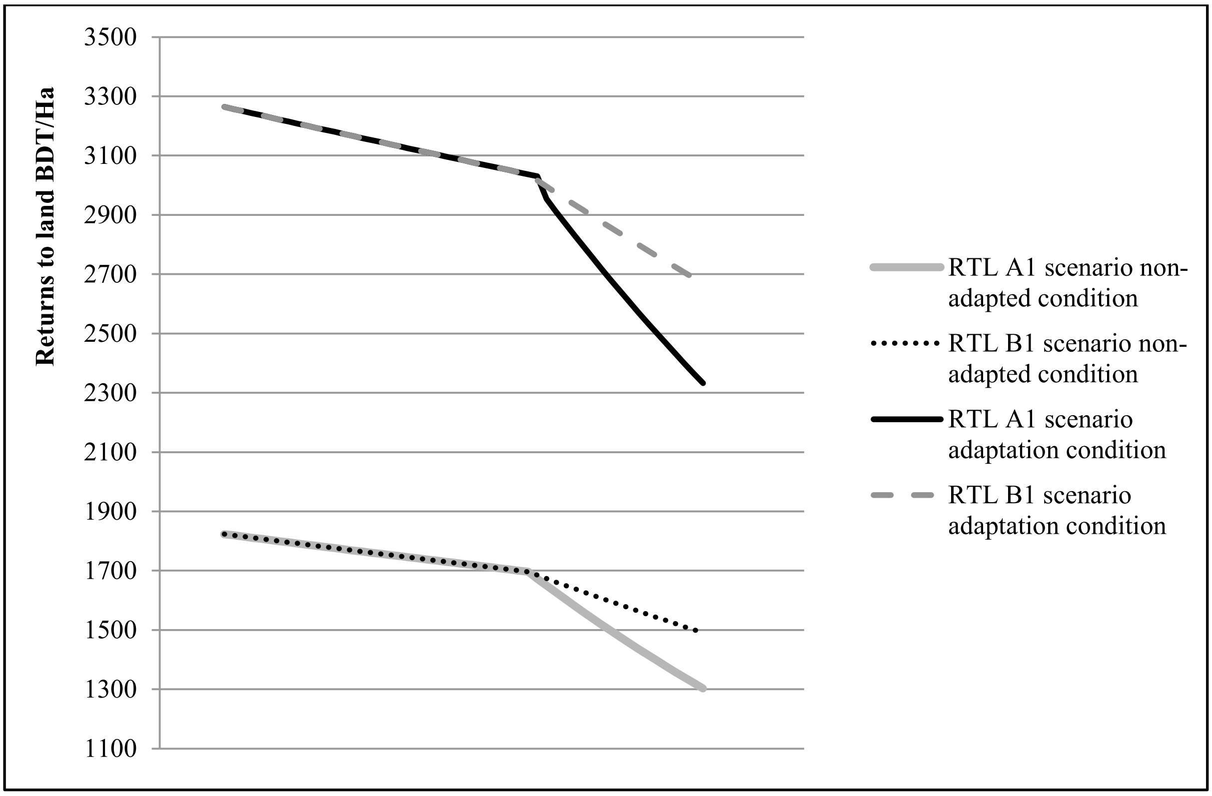
Source: Author's own calculation based on the survey

(b) Effect of future climate change on Amon returns to land

Figure 6.2 shows the development for the *Amon* season. The changes of climate parameters will lead to decreased returns to land in the period up to 2040.

After 2040 the effect of climate parameters will be more accelerated. Interestingly, figure 6.2 indicates that this will be for both adapted and non-adapted conditions, but the adapted farmers will have higher returns to land over time. Similar to the *Boro* season, adapted farmers will be in a better position despite declining trends.

Figure 6.1 Simulated returns to land of the Amon rice growing season in future climate scenarios



Source: Author own calculation based on survey

6.4 Intermediate conclusions

The objective of this chapter was to assess the impact of climate variability and adaptation options on farm earnings in future climate change scenarios. Farm earnings are represented by the returns to land. An advanced Ricardian approach using panel data was applied to assess the climate change impacts. The econometric models for *Amon* and *Boro* were fitted in relation to climate variability and other farm specific factors. In addition to this, from the estimated models impacts were predicted for different climate scenarios up to 2059.

Findings from the chapter reveal that the farming community will face significant climate change impacts. Currently, these effects are relatively insignificant, but in the future the bio-physical effects on production, hydrological balance, and human response will be very complex. The necessary adjustments by introducing soil crop management, fertility management and irrigation water management are promising options for farmers. Climate change is a continuous process changing present economic development, so alternative production systems by adaptation should be exploited by innovative research, policy-making and extension services.

7 Summary and conclusions

7.1 Introduction

The study assessed the economics of farm-level climate change and adaptation options of rice farming in coastal areas of Bangladesh. Based on the farm survey and a wide range of research, the adaptation options of farms were holistically evaluated. Surveying farmers of 300 farms from areas prone to the effects of the climate and with different climate thresholds, production information were recorded for an eight year period. Farm income susceptibility to climate, climate variability impact assessment on land returns, the economics of adaptation options, and the impact on productivity were analyzed and assessed in relation to future climate change. It was a study of climate impact assessment and adaptation impact assessment. The analytical part of this research covered the three major areas to gain an aggregate view of farm-level adaptation:

1. Insight into micro-level adaptation practice to climate variability and change: the case of rice farming in coastal areas of Bangladesh.
2. Economic implications of climate change impact and adaptation options in rice farming.
3. Impact of climate change and adaptation options on farm net income: A bio-economic analysis for future climate change projection.

7.2 Summary of findings

In the first steps of the study, the local level adaptation practice was evaluated in qualitative and descriptive measures. Farmers' perception of climate variability shocks were also supported by the agro-climatic data of the study area. 2006 was the year of their last normal production after that the farmers faced different climate variability stresses such as high temperatures, less precipitation in the dry season, variability of rainfall in the rainy season, and salinity intrusion. Farmers' production periods under shocks lasted almost three years from 2007 to 2009. Following this period, the sample farmers initiated alternative rice production techniques under the super-vision of extension agencies and NGOs.

The sample farmers autonomously selected their own effective alternative production system to avoid climate shock. For the *Amon* rice growing season they applied five distinct alternative ways to address shocks of high temperature, less precipitation, and salinity intrusion. Fifty percent of *Amon* rice growers adopted saline-tolerant seed varieties under the broad category of soil and crop management adaptation option. They found it to be faster and the easiest way to revive threshold production under shocks of climate variability. It also scored 1 out of 3 as an adaptation performance tool. The next most popular adaptation among the farmers was soil crop management with relay cropping with legume and balanced fertilizer use. It is a soil fertility management technique that introduces legume crop at the end of the major rice harvest. Approximately twelve percent of the studied farmers adopted this alternative production practice, which was scored 2 out of 3 as an adaptation performance practice by the responding farmers.

The third most popular adaptation option was soil and crop management through relay cropping, balanced fertilizer application and irrigation management by diversion ditches. This option was scored 3 out of 3 and only 13 percent of the farmers in the study adopted it for their *Amon* rice season. The fourth option was minimum or zero tillage-based integrated crop management with saline-tolerant varieties. This was scored 1 out of 3 and 13 percent of the *Amon* rice growers adopted it. The last one is minimum or zero tillage-based integrated crop management with saline-tolerant varieties, best fertilizer management practice by nitrogen. This technique was scored 2 by the sample farmers and only 12 percent adopted it.

In the *Boro* rice growing season there were nine categories of adaptations found in the survey. These are based on irrigation water harvesting and drainage management because this growing season is based on irrigation water. Most of the adaptation practices in the season ensure the saline-free irrigation water from underground. Soil and crop management practice with saline tolerant varieties that include best fertilizer management as well as irrigation water harvesting was scored 3 and 25 percent of the sample *Boro* rice growers adopted it. The next option is soil and crop management through saline tolerant-varieties and balanced fertilizer application by nitrogen deep placement with water harvest. This option also scored 3 as an adaptation performance technology and only 14 percent of the sample farmers adopted it. The third adaptation option was integrated crop management by saline-tolerant varieties, balanced fertilizer application with nitrogen deep placement as well as irrigation management by water reservoir and diversion ditches.

This integrated adaptation system was scored 3 and 15 percent of farmers applied it. The fourth adaptation in the *Boro* seasons was minimum tillage-based integrated crop management with saline-tolerant varieties. This used only one sub-component of adaptation and was scored by the farmers as 1 with only 3 percent of the sample farmers adopted it. The fifth adaptation option was best fertilizer management practice by a balanced fertilizer, nitrogen deep placement, including a water reservoir and diversion ditches. Seven percent of *Boro* rice grower applied this technique which scored 2 for adaptation performance.

The sixth adaptation option was the irrigation water management with water reservoir and diversion ditches to avoid the shock of climate variability. Approximately 10 percent of the sample *Boro* rice growers adopted it and scored 1. The seventh adaptation option was soil and crop management practice with saline-tolerant varieties associated with irrigation water management with water reservoir and diversion ditches, which scored 3 but only 7 percent of farmers could afford it. The zero tillage-based integrated crop management with saline-tolerant varieties with water reservoir and diversion ditches was the eighth adaptation options of the *Boro* grower. It scored 2 out of 3 and 12 percent sample farmers adopt this technique. The ninth adaptation was simple as it used only best fertilizer management practice by balanced fertilizer dose and scored a 1. Only six percent *Boro* rice growers applied it.

The second analytical part of the study focused on the economic implications of climate change impacts and adaptation options in rice farming. It was framed to identify relative merits of adaptation options using traditional farm management analytical tools and descriptive statistics also based on the survey data. An effective way of reviving the farm income to the threshold level by reducing the costs and increasing productivity widened the scope of agricultural adaptation. The diverse analysis of adaptation was conducted for the comparative economic performance of the alternative production options. Using instruments such as benefit cost ratio BCR analysis and cost effectiveness analysis CEA, the economic performance of the rice farmers' production in two seasons could be evaluated at different thresholds.

The third part of the study was the bio-economic analysis of farm earnings assessment under climate change and adaptation dynamics. It evaluated the effects of climate variability on returns to land from rice farming using panel data. A modified Advanced Ricardian approach was used to assess the impact of climate variables on land productivity. A fixed-effect balance panel model was applied to estimate the parameters and achieve the objective. The results of the estimated econometric model postulated that average maximum temperature had negative impacts on returns to land for both growing seasons. The precipitation as climate variable positively contributed to the returns to land for both growing seasons. The model also estimated the adaptation performance score on the land productivity. This confirmed that the marginal impact of successive adaptation option for both seasons decreased risk and had a positive effect on returns to land.

Another important finding of part three is the assessment of the impact of the future global climate scenarios specific to southwest coastal rice farming of Bangladesh. This study used the temperature and precipitation forecast up to 2060. After conducting a simulation under two climate change scenarios based on these circulation models, the estimated returns to land visualized the impacts of climate change and adaptation for both the future highest emission trajectory (A1F1) and the lowest emission trajectory (B1). The projections were made under assumptions of adaptation option possibilities. For both rice growing seasons, the different trajectories imply a declining trend of returns to land under climate change. For future impacts, if the rice grower practicing adaptations to avoid the shocks of climate change they will be in a better position with production performance despite the declining trends for continuous climate change.

7.3 Conclusions

The study of climate change is interlinked with a versatile range of knowledge, from space physics to social science. The state of economics for analyzing the issue is only light bearing to see the limits of growth and the compromises of interest groups for the optimization of resources. Undoubtedly, industrialization brought about benefits to civilization, but at the cost to our future environment. Every production in modern society now operates in the challenge of future climate change and related bio-physical conditions. Growth in every sector is accompanied by emissions and atmospheric CO_2 concentrations, which is the leading factor in global climate change and temperature rise. Traditional livelihoods, such as agriculture still exist in developing countries where the production system depends on nature and the hydro-climate. Any adverse shocks relating to the climate created from industrial development may damage these communities and their production system first: Their livelihoods and production systems are entirely dependent on bio-ecological conditions of the earth. The impact assessment of climate change and adaptation on agriculture is worthwhile only when it focuses on farm-level activities and their alternations in response to weather variability. The farmers practice adaptation options with the main motivation of productivity resilience up to the threshold level. However, there are some other auxiliary motivations such as sound farm practice for climate change mitigation and wise use of nutrients and water resources.

They also choose the adaptation options according to their affordability and available resources. The higher cost of investment in adaptation will ensure high productivity, but the cost-effectiveness is an important factor to consider. Climate change is a continuous process so the farm-level adaptations should be continuously checked and reviewed according to climate forecast. The private micro-level adaptation has a positive impact on farm earnings by their autonomous initiatives; it would be rigorous when public adaptations take place in coastal communities. Therefore, the combined effect of public and private investment to adaptation will be a great initiative for facing climate change in farm businesses.

7.3.1 Contribution of research work

The basic contribution of the research will be knowledge-sharing for climate-smart agriculture. From the field experience, low-carbon farming and the mitigation potential of system adaptation can be identified from the study. These empirical findings of climate change adaption at the farm level will support farm and crop specific efficiency. These impacts are related to forthcoming climate events. The study will also contribute to the field-oriented input-output relationship associated with climatic, economic and bio-physical factors. These parameters will be used to develop a comprehensive adaptation perspective for forecasting future agricultural effects in response to climate change.

The assessment results of adaption options would contribute to the climate justice debate with respect to the Bangladesh agricultural sector. From the estimated effect on the micro level data could be aggregated to quantify the welfare loss of the sector. The climate change policy instrument relating to agriculture will benefit by the findings of the research. Finally it will help to set priorities for future climate change adaptation and mitigation.

7.3.2 Limitations of the study

The empirical study always has a number of limitations relating to assumptions and cognitive responses of respondents. This study, as an empirical work, could not fully avoid such problems as the perceptive accuracy of the honest responses from the field. However, it repeatedly checked and cross-checked the data and records to minimize errors in the assumptions. The farmers sometimes provided the information of crop production from their memory, which might have a great influence taken after analysis. Their motivation to adopt alternative adaptation option may be influenced by the extension monitoring and support. However, after the withdrawal of awareness and promotional activities of GO and NGOs, what would be the real consequence is a question.

The study used climate data of the nearest weather stations instead of farm-specific information. This is one of the notable assumptions and limitations of the study. The terms adaptation and climate change are complex and multidimensional; a single study discipline is not sufficient for climate change and assessing adaptation options in farming. The economic framework to analyze the two basic components could not quantify, for example, the inherent soil quality damage and the ecological diversity loss. However, it is reality that the climate variability or significant change in quality is influencing factors of farm income. In monetary terms we estimate returns to land that are influenced by climate change and adaptation, but institutional settings, development of the economy, redistribution of welfare, scope of agricultural international trade and favorable agricultural terms of trade may help to improve returns to land despite climate shock. Considering the existing short-comings of this present study, the story of agricultural distortions and determinants of farm-level adaptation to climate change could require a comprehensive theoretical perspective. These implications may pave the way for a future research agenda.

7.3.3 Future research agenda

The objectives of the study were a regional specific assessment in a coastal area where climate variability appeared in notable form. A scope for further research would be a moderate climate-prone area out of a coastal zone. The agriculture of the study area was already facing a different climate and non-climate shock which allows a comparison when another area is assessed in the same way for the effects of climate variability. Incidentally, the study areas only cultivate rice as the main crop in two seasons, but there are diverse crops grown in Bangladesh. In addition to this other components of agriculture are available in the farming system, for example livestock, poultry and fisheries. Therefore, considering each and every component of agriculture, future research could assess component-specific adaptations.

This study did not quantify the mitigation potential of adaptation practice options. The adaptation options have merits for cost or resource savings, potential for GHG mitigation, and productivity gains both financially and economically. Analyzing farm-level data, future research could assess the climate change adaptation option impact on the basis of water footprints or carbon footprints. Using partial equilibrium analysis of economic theory, the welfare losses or gains due to adaptation options could be a new dimension of future research. Then, the effect on the supply side for climate change adaptation could be quantified and the net effect estimated by welfare analysis. This study conducted micro-level analysis with survey data. For future research it would be worthwhile when the national level input-output data and climate variables are analyzed in the same way, resulting in national data of published sources of vulnerability and adaptations impacts. Most countries in the world provide subsidies to agriculture for correcting the distortion. They sometime need to set priorities for better utilization of public funds and cost-effectiveness of resources. The future research agenda could analyze the policy instruments for sound climate-friendly farming practice as opposed to controlling the GHG from the agriculture sector.

References

Adams, R. M., B. H. Hurd, S. Lenhart and N. Leary (1998): Effects of global climate change on agriculture: An interpretative review. Climate Research 11 (1): 19-30.

Adger, W. N., S. Agrawala, M. M. Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smith and K. Takahashi (2007): Assessment of adaptation practices, opinions, constraints and capacity. In: Climate change 2007: Impacts, adaptation and vulnerability, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, C. E. Hanson and P. J. van der Linden. Contribution of working group II to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge: 717-743

Adger, W. N., S. Huq, K. Brown, D. Conway and M. Hulme (2003): Adaptation to climate change in the developing world. Progress in Development Studies 3: 179-195.

AGHGO (Australian Greenhouse Office)(2004): Economic Issues Relevant to Costing Climate Change Impacts. Australian Greenhouse Office AGHGO, Canbera.

Ahmad, Q. K. and R. A. Warrick (2001): Methods and Tools. In: Climate change 2001: Impacts, adaptation, and vulnerability, edited by J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokke and K. S. White. Contribution of working group II to the third assessment report of the IPCC. Cambridge Univesity Press, Cambridge: 105-143.

Ahsan, S., M. S. Ali, M. R. Hoque, M. S. Osman, M. Rahman, M. J. Babar, S. A. Begum, D. M. Rahman and K. R. Islam (2001): Agricultural and Environmental Changes in Bangladesh in Response to Global Warming. In: Climate change and food security in South Asia, edited by R. Lal, M. V. K. Sivakumar, S. M. A. Faiz and A. H. M. M. Rahman and K. R Islam. Springer, The Netherlands: 119-134.

Ali, A. (1999): Climate change impacts and adaptation assessment in Bangladesh. Climate Research 12 (2): 109-116.

Antle, M. J. and S. M. Capalbo (2010): Adaptation of agricultural and food system to climate change: An economic and policy perspective. Applied Economic Perspectives and Policy 32 (3): 386-416.

Azam, M. S. and K. S. Imai (2009): Vulnerability and Poverty in Bangladesh. Working paper of Australia and South Asia Research Centre ASARC, no 2009/02.

Baltagi, B. H. (2008): Econometrics. Springer Verlag, Berlin, Heidelberg.

Bangladesh Economic Review (2012): Bangladesh Economic Review. Economic Adviser's Wing, Finance Division, Ministry of Finance, Government of the People's Republic of Bangladesh, Dhaka 2012.

Banglapedia (2013): http//www.banglapedia.org/Atlas/bangladesh.htm. Last accessed: 21.12.2013.

— (2014): http://www.banglapedia.org. Last accessed: 01.25. 2014.

BARC (Bangladesh Agricultural Research Council) (2005): Fertilizer Recommndation Guide; Soils Publication No. 45. BARC, Dhaka.

Barnwal, P. and K. Kotani (2010): Impact of variation in climate factors on crop yield: a case of rice crop in Andhra Pradesh, India. Working paper. International University of Japan IUJ Research Institute.

Basak, J. K. (2010): Future Fertiliser Demand for Sustaining Rice production in Bangaldesh: A Quantatative Analysis. Unnayan Onneshan-The Innovators, Dhaka.

Basak, J. K., R. A. M. Titumir and N. C. Dey (2013): Climate change in Bangladesh: A historical analysis of temperature and rainfall data. Journal of Environment 2 (2): 41-46.

BBS (Bangladesh Bureau of Statistics) (2004): Stastistical Year Book of Bangladesh. Ministry of Planing; Goverment of the People’s Republic of Bangladesh, Dhaka.

— (2008): Stastistical Year Book of Bangladesh. Ministry of Planing; Goverment of the People’s Republic of Bangladesh, Dhaka.

Blaikie, N. W. H. (2010): Designing Social Research. Polity Press, Cambridge.

BRRI (Bangladesh Rice Research Institute) (2014): Dhan Utpadoner Krishok Proshikhon Flip Chart. http://knowledgebank-brri.org/Publications/Rice-Flip-Charts.pdf. Last access: 01.01.2014.

Bryan, E., C. Ringler, B. Okoba, J. Koo, M. Herrero and S. Silvestri (2011): Agricultural management for climate change adaptation, greenhouse gas mitigation, and agricultural productivity: Insight from Kenya. IFPRI discussion paper no 01098. International Food Policy Researc Institute IFPRI, Washington, DC.

CEGIS (Center for Environment and Geographical Information) (2013): Climate change impacts, vulnerability and adaptation: Sustaining rice production in Bangladesh. Report on water availability assessment using SWAT Model. CEGIS, Dhaka.

Climate Institute (2014): Ocean and Sea Level Rise: Consequences of climate change on the oceans. http://www.climate.org/topics/sea-level. Last accessed 15.05. 2014.

Cruz, R. V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li and N. Huu Ninh (2007): Asia. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change IPCC. Cambridge University Press, Cambridge: 469-506.

Deressa, T., R. Hassan and D. Poonyth (2005): Measuring the impact of climate change on South African agriculture: the case of sugarcane growing regions. Agrekon 44 (4): 524-542.

Deressa, T. T., R. M. Hassan and C. Ringler (2009): Assessing household vulnerability to climate change. IFPRI discussion Paper no 00935. International Food Policy Research Institute IFPRI, Washington, DC.

Deryng, D., W. J. Sacks, C. C. Barford and N. Ramankutty (2011): Simulating the effect of climate change and agricultural management practices on global crop yield. Global Biogeochem. Cycles 25, GB 2006, doi:10.1029/2009GB003765.

Deschenes, O. and M. Greenstone (2007): The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. American Economic Review 97 (1): 354-385.

Di Falco, S. M. Veronesi and M. Yesuf (2011): Does adaptation to climate change provide food security? A micro-perspective from Ethiopia. American Journal of Agricultural Economics 93 (3): 829-846.

Di Falco, S., M. Yesuf , G. Kohlin and C. Ringler (2012): Estimating the impact of climate change on agriculture in low-income countries: Household level evidence from the Nile Basin, Ethiopia. Environmental Resource Economics 52: 457-478, doi:10.1007/s10640-011-9538-y.

Dillon, J. I. and J. B. Hardaker (1980): Farm Management Reseach for Small Farmer Development. Food and Agriculture Organization FAO of United Nations, Rome.

Downing, T. E. (1991): Vulnerability to hunger in Africa: A climate change perspective. Global Environmental Change 1: 355-380.

Fankhauser, S., R. S. J. Tol and D. W. Pearce (1997): The aggregation of climate change aamages: A welfare theoretic approach. Environmental and Resource Economics10: 249-266.

FAO (Food and Agriculture Organization)(2006): Livelihood adaptation to climate variability and change in drought-prone areas of Bangladesh. The Food and Agriculture Organization FAO of United Nations, Rome.

— (2011): Bangladesh and FAO Achievements and Success Stories. Country Report of the Food and Agriculture Organization FAO of United Nations. Rome.

Gilbert, G. N. (2008): Reaching Social Life. Sage Publications Ltd, London.

Gine, X, R. M. Townsend and J. Vickery (2007): Rational expectations? Evidence from planting decisions in Semi-arid India. Working paper. The World Bank (DECRG), University of Chicago and Federal Reserve Bank, New York.

GOB (Government of Bangladesh) (2005): Comendium of Environment Stastistics of Bangladesh. Ministry of Planning, Government of Bangladesh GOB, Dhaka.

Greene, W. H. (2008): Econometric Analysis. 6th edition. Prentice Hall, Upper Saddle River New Jersey.

Harmeling, S. (2008): Global Climate Risk Index 2009: Weather-related loss and their impacts on countries in 2007 and in a long-term comparision. Germanwatch, Berlin.

Hertel, T. W., M. B Burke and D. B. Lobell (2010): The poverty implication of climate-induced crop yield changes by 2030. Purdue University: unpublished manuscript.

Hertel, W. T. and S. D. Rosch (2010): Climate change, agriculture, and poverty. Applied Economic Perspectives and Policy 32 (3): 355-385.

Hsiao, C. (2008): Analysis of Panel Data. 2nd ed. Cambridge University Press, Cambridge.

Huda, F. A. and M. A. Khan (2014): Policy instruments for reducing nitrogen fertilizer-based emission: Under policy conflict of self-sufficiency of food versus sustainable management of agriculture. Journal of Earth Science and Climatic Change 4-5 (6): 207, doi:10.4172/2157-7617.1000207207.

Huq, S., A. U. Ahmed and R. Koudstaal (1996): Vulnerability of Bangladesh to climate change and sea level rise. In: Climate change and world food security. NATO ASI Series, I 37, edited by T. E. Downing. Springer-Verlag, Berlin, Heidelberg: 347-379.

IPCC (Intergovernmental Panel on Climate Change) (2003): Climate Change : The IPCC 1990 and 1992 Assessments. Supplement of the Intergovernmental Panel on Climate Change IPCC, Geneva.

— (2005): Impacts, adaptation, and vulnerability: Climate Change 2001. Third assessment report of the Intergovernmental Panel on Climate Change IPCC. Cambridge University Press, Cambridge 2005.

— (2007a): IPCC Fourth Assessment Report: Climate Change 2007. Synthesis report. https://www.ipcc.ch/publications_and_data/ar4/syr/en/spms3.html. Last accessed 21.02.2014.

— (2007b): Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change IPCC. Cambridge University Press, Cambridge.

— (2013): IPCC Fifth Assessment Report (AR5). www.ipcc.ch/ipccreports/assessments-reports.htm. Last accessed 30.05.2014.

— (2014): Climate Change 2014: Impact, adapataion, and vulnerability: Summary for Policy Maker. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change IPCC. Cambridge University Press, Cambridge.

Isik, M. and S. Devadoss (2006): An analysis of the impact of climate change on crop yields and yield variability. Applied Economics 38 (7): 835-844.

Islam, M. M., S. Sallu, K. Hubacek and J. Paavola (2014): Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: insights from coastal Bangladesh. Regional Environmental Change 14 (1): 281-294.

Just, R. E. and R. D. Pope (1979): Production function estimation and related risk considera-tions. American Journal of Agricultural Economics 61 (2): 276-284.

Kandlinkar, M. and J. Risbey (2003): Agricultural risk models: Adequacy of data, models and issue. American Journal of Agricultural Economics 85 (5): 1249-1256.

Karim, Z., S. G. Hussain and M. Ahmed (1996): Assessing impacts of climate variations on food grain production in Bangladesh. Water, Air, and Soil Pollution 92: 53-62.

Kelly, P. M. and W. N. Adger (2000): Theory and practice in assessing vulnerability to climate change and facilitating adaptation. Climate Change 47 (4): 325-52.

Kiptot, E., P. Hebinck, S. Franzel and P. Richard (2007): Adopters, testers or pseudo adopters? Dynamics of the use of improved tree fallows by farmers in Western Kenya. Agricultural Systems 94: 509-519

Kreft, S. and D. Eckstein (2014): Global Climate Risk Index 2014. Briefing paper, Germanwatch, Berlin.

Ladha, J. K. (1992): Biological Nitrogen Fixation for Sustainable Agriculture. Kluwer Academic Publishers, Dordrecht.

Lobell, D. B. and C. B. Field (2007): Global scale climate-crop yield relationships and the impacts of recent warming. Environmental Research Letters 2: 014002.

Mahmood, R. (1997): Impacts of air temperature variations on the boro rice phenology in Bangladesh: Implications for irrigation requirements. Agricultural and Forest Meteorology 84 (3-4): 233-247.

Massetti, E. and R. Mendelsohn (2010): Estimating Ricardian Models With Panel Data. Plenary paper at IATRC public trade policy research and analysis symposium on Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security. University of Hohenheim, Stuttgart.

— (2011): The impact of climate change on U.S. agriculture: a cross-section, multi-period, Ricardian analysis. In: Handbook on Climate Change and Agriculture, edited by A. Dinar and R. Mendelsohn. Edward Elgar Publishing, New Haven: 301-319.

— (2012): Estimating Ricardian Models With Panel Data. http://cbey.yale.edu/uploads/ Environmental%20Economics%20Seminar/Massetti_RicardianClimateChange-preview.pdf. Last accessed 31.12.2013.

McCarl, B. A., X. Villavicencio and X. Wu (2008): Climate change and future analysis: Is stationarity dying? American Journal of Agricultural Economics 90 (5): 1241-1247.

McCathy, J. J., O. F. Canziani, N. A. Leary, D. J. Dokken and K. S. White (2001): Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge.

Mendelsohn, R. (2009): The impact of climate change on agriculture in developing countries. Journal of Natural Resources Policy Research 1 (1): 5-19.

Mendelsohn, R., A. Basist, A. Dinar, P. Kurukulasur and C. Williams (2007): What explains agricultural performance: Climate Normals or Climate Variance? Climatic Change 81 (1): 85-99.

Mendelsohn, R., A. Dinar and A. Sanghi (2001): The effect of development on the climate sensitivity of agriculture. Environmental Development Economics 6: 85-101.

Mendelsohn, R. and A. Dinar (2003): Climate, water, and agriculture. Land Economics 79: 328-341.

Mendelsohn, R., W. Nordhaus and D. Shaw (1994): The impact of global warming on agriculture: A Ricardian analysis. American Economic Review 84: 753-771.

Mertz, O., S. K. Halsnae, J. E. Olesen and K. Rasmussen (2009): Adaptation to climate change in developing countries. Environmental Management 43 (5):743-52.

MOEF (Ministry of Environment and Forest)(2005): National Adaptation Program of Action (NAPA). Ministry of Environment and Forest (MOEF), Government of People's Republic of Bangladesh, Dhaka.

Molua, E. L. (2009): An empirical assessment of the impact of climate change on smallholder agriculture in Cameroon. Global and Planetary Change 67 (3-4): 205-208.

Nelson, G. C., M. W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu and C. Ringler (2009): Climate change: Impact on agriculture and cost of adaptation. IFPRI report of September 2009. International Food Policy Research Institute, Washington, DC.

Nordhaus, W. D. (1994): Managing the Global Commons: The Economics of Climate. MIT Press, Cambridge.

Pervin, M. (2013): Mainstreaming climate change resilience into development planning in Bangladesh. Country Report on April 2013. Institute of Environment and Development (IIED), London.

Quiggin, J. and J. K. Horowitz (1999): The impact of global warming on agriculture: A Ricardian analysis: Comments. American Economic Review 89: 1044-1045.

Ramasamy, S. (2012): Climate risk assessment and management in agriculture. Building resilience for adaptation to climate change in the agriculture sector. Food and Agriculture Organization (FAO) of United Nations, Rome.

Rasel, H. M., M. R. Hasan, B. Ahmed and M. S. U. Miah (2013): Investigation of soil and water salinity, its effect on crop production and adaptation strategy. International Journal of Water Resources and Environmental Engineering 5 (8): 475-481.

Rashid, A. K. M. M., D. Sinha and H. Imam (2009): Climate Change Vulnerability in Bangladesh Strategic Position of DSK/DCA in the Field of Climate Change Adaptation Initiatives in Bangladesh. Dustha Shansta Kendra DSK and Dan Church Aid DCA, Dhaka.

Rashid, M. H. and M. S Islam (2007): Adaptation to Climate Change for Sustainable Development of Bangladesh Agriculture. Bangladesh Rice Research Institute (BRRI), Gazipur.

Rawlani, A. K. and B. K. Sovacool (2011): Building responsiveness to climate change through community based adaptation in Bangladesh. Mitigation and Adaptation Strategies for Global Change 16: 845-63.

Rayhan, M. I. and U. Grote (2010): Crop diversification to mitigate flood vulnerability in Bangladesh: An economic approach. Economics Bulletin 30 (1): 597-604.

Rebot, J. C. (1995): Casual structure of vulnerability: Its application to climate impact analysis. Geo Journal 35 (2): 119-122.

Reid, S., B. Smit, W. Caldwell and S. Belliveau (2007): Vulnerability and adaptation to climate risks in Ontario agriculture. Mitigation and Adaptation Strategies for Global Change 12 (4): 609-637.

Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izuarralde, S. Jagtap, J. Johnes, L. Mearns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg and C. Rosenzweig (2003): U.S. Agriculture and climate change : New results. Climate Change 57: 43-69.

Ricardo, D. (1817): On the Principles of Political Economy and Taxation. John Murray, London.

Rosenzweig, M. R. and H. P. Binswanger (1993): Wealth, weather risk and the composition and profitability of agricultural investments. The Economic Journal 103 (416): 56-78.

Rowhani, P. and N. Ramankutty (2009): Crop Modeling. Paper presented at the workshop of climate volatility, agriculture variability and poverty vulnerability, October 20, 2009. The World Bank Washington, DC. http://go.worldbank.org/HHBFKLDG40. Last accessed 20.12.2013.

Sachs, J. T., Panatayou and A. Peterson (1999): Developing countries and the control of climate change: A theoretical perspective and policy implications. CAER II discussion paper, no 44. Harvard Institute for International Development HIID, Cambridge, MA.

Sarker, M. A. R. (2012): Impacts of Climate Change on Rice Production and Farmers' Adaptation in Bangladesh. An unpublished PhD dissertation at the School of Accounting, Economics and Finance, University of Southern Queensland, Queensland.

Sarker, M. H. (2005): Assessment of spatial trend of soil salinityin southwest region of Bangladesh using GIS techniques. Ecology division, Center for Environmental and Geographic Information Services CEIGIS, Dhaka.

Schlenker, W. and D. B. Lobell (2010): Robust negative impacts of climate change on African agriculture. Environmental Research Letters 5: 014010.

Schlenker, W., W. M. Hanemann and A. C. Fisher (2006): The impact of global warming on U.S. agriculture: An econometric analysis of optimal growing conditions. Rev Econ Stat 88 (1): 113-125.

Schlenker, W. and M. J. Roberts (2006): Nonlinear effects of weather on corn yields. Review of Agricultural Economics 28 (3): 391-398.

Smit, B. and J. Wandel (2006): Adaptation, adaptive capacity and vulnerability. Global Environmental Change 16 (3): 282-292.

Smit, B., O. Pilifosova, I. Burton, B. Challenger, S. Huq, R. J. T. Klein and G. Yohe (2001): Adaptation to Climate Change in the Context of Sustainable Development and Equity. Cambridge University Press, New York.

SMRC (SAARC Meteorological Reseach Council)(2003): The Vulnerability Assessment of the SAARC Coastal Region due to Sea Level Rise: Bangladesh Case. SAARC Meteorological Reseach Council SMRC publication no.3, Dhaka.

Titus, J. G. (1990): Greenhouse effect, sea level rise, and land use. Land Use Policy 2: 138-153.

Tubiello, F. N. and C. Rosenzweig (2008): Developing climate change impact metrics for agriculture. The Integrated Assessment Journal 8 (1):165-184.

Tyndall, B. (1996): The Socioeconomics of Grevillea robusta within the Coffee Land-Use System of Kenya. Report no. 109 of Agroforestry Research Networks for Africa AFRENA, Nairobi.

UNDP (United Nations Development Programme) (2007): Human Development Report 2007/2008: Fighting Climate Change: Human Solidarity in a Divided World. Palgrave Macmillan, New York.

Van Huylenbroeck, G. and M. Calus (2008): Farm Management Exercise. Faculty of Bio-Science Engineering, Ghent University. Class lecture materials offers on September 15, 2008.

Wang, J., R. Mendelsohn, A. Dinar, J. Huang, S. Rozelle and L. Zhang (2009): The impact of climate change on China’s agriculture. Agricultural Economics 40: 323-337.

Wikipedia (2014): Cost-effectiveness. wikipedia.org. http://en.wikipedia.org/wiki/Cost-effectiveness. Last accessed 21.05.2014.

World Bank (2000): Bangladesh Climate Change and Sustaitable Development. Report no. 21104-BD-Dhaka of the South Asia Rural Development ASARD unit of the World Bank, Washington, DC.

— (2009): Convenient Solutions to an Inconvenient Truth: Ecosystem-based Approaches to Climate Change. Special Report of the World Bank.,Washington, DC.

Yamin, F., A. Rahman and S. Huq (2005): Vulnerability, adaptation and climate disasters: a conceptual overview. IDS bulletin 36: 1-14.

Ziervogel, G., S. Bharwani, and T. E. Dowining (2006): Adapting to climate variability: Pumpkins, people and policy. Natural Resource Forum 30 (4): 294-305.

Appendices

Appendix 1 Questionnaire used for the farm survey

Title: Economic Assessment of Farm Level Climate Change Adaptation Options: Analytical Approach and Empirical Study for the Coastal Area of Bangladesh

Questionnaire used for the farm survey

Introductory statement:
This survey is carried out for PhD research in the Chair for Agricultural Policy, Dept. of Agricultural Economics Humboldt University of Berlin Germany.

1. Identification of the farmer: 1.1. Name: Sample no.

1.2 Age 1.3 Education 1.4 Address 1.4.1 Village 1.4.2 Upazila 1.4.3 District 1.4.4 Mobile. No. (if any)	

2. Household characteristics

2.1	Family size:	a. Adult Male	b. Adult Female	c. Child
2.2	Occupation	a. Main	b. Subsidiary	
2.3	Farm size (in decimal):	a. Own land	b. Renter in	c. Rented out

2.4 Assets

Household Asset	No.	Acquisition price	Replacement Cost	Life & year of Acquisition	Salvage Value	Productive Asset	No.	Acquisition price	Replacement cost	Life & year of Acquisition	Salvage Value
1. Primary residence made of Tine sheet, or brick						14. Hoe					
2. Primary residence with mud and tin roof material						15. Wooden Plough					
3. Toilet						16.Power tiller					
4. Car(s)						17. Wider					
5. Motorcycle						18. Ladder					
6. Refrigerator						19. Reaper					
7. Television						20. Harvester					
8. Radio						21. Sprayer					
9. Cell phone						22. Irrigation pump					
10. Bicycle(s)						23. Tractor					
11. Gold/ jewelry						24.Lorry					
12. Modern mattress						25. boat					
13. Furniture’s						26. Husking Machine					

2.5 Livestock inventory of farms

Animals	Closing year		Beginning Year	
	No	Value	No	Value
No. of Cattle				
Goat & Sheep				
Indigenous Chicken				
Duck				
Pigeon				

2.6 Access to basic facilities

2.6.0: Type of Facility	2.6.1 Do you currently have access? (1: Yes; 2: No)	2.6.2 Distance (km)	2.6.3 Beginning year
Electricity			
Telephone (land line)or Mobile			
Primary School			
Secondary School			
Medical center			
Drinking water/ Irrigation water			
Solar Energy/ Gas			
Market for Inputs			
Market for Produce			
Market for household need			
Public Extension Service			
NGO Extension Service			
Bank or Credit NGOs			

2.7 Social capital

2.7.1 Is anyone in your household a member of a community/village association?
____________________(1: yes; 2: no).

If yes,

2.7.1.1 Who is a member of the associations?	2.7.1.2 Which associations?	2.7.1.3 When joined? (year)	Service Explore from the Association

3. Land utilization patterns

Categories of land and plot	Net sown Area			Irrigation status	Crops grown in the last years (2006-2010)												
					June- July	Jul -Aug	Aug -Sept.	Sept.-Oct	Oct-Nov	Nov-Dec	Dec-Jan	Jan/ Feb	Feb-Mar	Mar-April	April May	May-June	Any Change
	Threshold	Non-adapted	Adapted														
Crop land: 1.																	
2.																	
3.																	
4.																	
5.																	
6.																	
7.																	
8.																	
9.																	
10.																	
Orchard																	
fallow																	
pond																	
Homestead																	
Gher																	

4. Agro-climatic data:

Climate Event	Months													
	June July			Jul. Aug.	Aug. Sept.	Sept. Oct	Oct. Nov	Nov. Dec	Dec. Jan	Jan. Feb	Feb. March	March. April	April. May	May June
	min	max	Average											
Temperature Celsius														
Precipitation rain fall (mm)														
Humidity (%)														
Salinity Level														
Flooding														

5. Agro economic data

5.1 Rabi season

Item \ Adaptation Status	Threshold	Without Adaptation	Adaptation	Threshold	Without Adaptation	Adaptation	Threshold	Without Adaptation	Adaptation	Nature of adaptation ranked by the farmer
Human labor (Man-days)										
Family Male Female										
Hired										
Total labor										
Wage rate (Tk.)										
Human lab cost										
Draft power										
Family (pair-day)										
Hired (pair day)										
Total (pair day)										
Hiring rate (Tk)										
Cost of draft power										
Power tilling cost										
Material inputs										
Seed/Seedling										
Own										
Purchased										
Price of seed										
Cost of seed/seedling										
Fertilizer and manure										
Urea (qty)										
Price										
TSP										
Price										
MP										
Price										
Manure										
Price										
Total cost of Fertilizer & manure										
Insecticides cost										
Water charge										
Rental value of land										
Output:										
Quantity										
Price										
Value of by product										
Value of the total return										
Total net return										

5.2 *Kharif-1* season (April-June)

Adaptation Status / Items	Threshold	Without Adaptation	Adaptation	Threshold	Without adaptation	Adaptation	Threshold	Without adaptation	Adaptation	Nature of adaptation ranked by the farmer
Human labor (Man-days)										
Family Male Female										
Hired										
Total labor										
Wage rate (Tk.)										
Human lab cost										
Draft power										
Family (pair-day)										
Hired (pair day)										
Total (pair day)										
Hiring rate (Tk)										
Cost of draft power										
Power tilling cost										
Material inputs										
Seed/Seedling										
Own										
Purchased										
Price of seed										
Cost of seed/seedling										
Fertilizer and manure										
Urea (qty.)										
Price										
TSP										
Price										
MP										
Price										
Manure										
Price										
Total cost of Fertilizer & manure										
Insecticides cost										
Water charge										
Rental value of land										
Output:										
Quantity										
Price										
Value of by product										
Value of the total return										
Total net return										

5.3 *Kharif-II* (July-October)

Crop and variety / Item										
	Threshold	Without Adaptation	Adaptation	Threshold	Without Adaptation	Adaptation	Threshold	Without Adaptation	Adaptation	Nature of adaptation ranked by the farmer
Human labor (Man-days)										
Family Male Female										
Hired										
Total labor										
Wage rate (Tk.)										
Human lab cost										
Draft power										
Family (pair-day)										
Hired (pair-day)										
Total (pair-day)										
Hiring rate (Tk.)										
Cost of draft power										
Power tilling cost										
Material inputs										
Seed/Seedling										
Own										
Purchased										
Price of seed										
Cost of seed/seedling										
Fertilizer and manure										
Urea (qty.)										
Price										
TSP										
Price										
MP										
Price										
Manure										
Price										
Total cost of Fertilizer & manure										
Insecticides cost										
Water charge										
Rental value of land										
Output:										
Quantity										
Price										
Value of by product										
Value of the total return										
Total net return										

6. Information of weather shock to farm

6.1 Which weather shocks have affected your farm and household during the last 5 years?

6.1.1	6.1.2	6.1.3	6.1.4	6.1.5	6.1.6	6.1.7	6.1.8
Type of shock (key)	**When was the shock (year in last 5 years)**	**What did the shock result in? (Key)**	**What was most affected shock?**	**What did you do - Action? (Key)**	**How took the action?**	**How widespread was the shock? (Key)**	**Estimate of the amount of loss to the farm**

Key for 6.1.1 Type of climate shock	**Key for 6.1.5 Action**	11: HH plus others migrated to rural area,
1: Loss of assets,	1. Did nothing,	12: Migrated to urban area,
2. Loss of income	2: Sold livestock,	13: Sought off-farm employment,
3. Decline in crop yield	3. Sold crops	14: Eat less;
4. Death of livestock	4. Sold land/home	15: Eat different foods
5. Food shortage/insecurity	5. Sold assets	16. Kept children home from school
6. Other [specify]_________	6: Borrowed from relatives or friends	17: Other [please specify] ___
Key for 6.1.3 Outcome of Shock:	7: Borrowed from bank,/NGO	**Key for 6.1.7 How widespread**
1. Sea Flood	8. Borrowed from private money lenders	1: only my HH,
2. Water Stagnation	8: Received food aid,	2: some HH in village,
3. Salinity in the field	9: Participated in food for work,	3: all HH in village,
4. Shortage of irrigation	10: HH head migrated to other rural area	4: many HH in district
5. Others.		5. Others

<table>
<tr><th colspan="3">6.2 When was the first following shocks you experienced?</th><th colspan="3">6.3 When was the last year you had too much rain? ____________(year)</th></tr>
<tr><td colspan="2">6.2.1 During the last large drought, did you change your farming practice (crop and livestock)? _______ (yes: 1, no: 2)</td><td></td><td colspan="3">6.3.1 During the last year with too much rain, did you change your farming practice (crop and livestock)? ________ (yes:1, no: 2)</td></tr>
<tr><td>6.2.2 If yes, what did you do? (key)</td><td>6.2.3 If yes, how? (key)</td><td></td><td></td><td>6.3.2 If yes, what did you do? (key)</td><td>6.3.3 If yes, how? (key)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

7. Information of adaptations:

7.1 Nature of adaptation: Investment information of Adaptation:

Name of adaptation	Initial investment	Repair and maintenance cost	Life	Yearly benefit	Yearly cost

7.2 Adaptation keys

Key for crop management. How did you change your farming practices in response to drought/ too much rainfall?:	Rank	Key for Fertilizer best management practice and irrigation water management	Rank
No change		2.1 Nitrogen deep placement	
1.1 Seed variety change (shock -tolerance)		2.2 Change from crop to livestock production	
1.2 Zero or minimum tillage		3.1 Wet Drying Technique by diversion ditches or canals	
1.3 Relay cropping with legumes		3.2 Water harvesting by water reservoir or DTW	
Others			
4.1.1 Increase amount of land under production		4.1.11 Change pattern of animal consumption	
4.1.2 Reduce amount of land under production		4.1.12 Increase the number of livestock	
Change field location		4.1.13 Decrease the number of livestock (de-stocking)	
4.1.4 Implement soil and water management techniques		4.1.14 Diversify livestock feeds	
4.1.5 Change fertilizer application		4.1.15 Change livestock feeds	
4.1.6 Build a water harvesting scheme		4.1.16 Supplement livestock feeds	
4.1.7 Build a diversion ditch		4.1.17 Change veterinary interventions	
4..1.8 Plant trees for shading		4.1.18 Change portfolio of animal species	
4.1.9 Irrigate more		4.1.19 Change animal breeds	
4.1.10 Surface Water management		4.4.20 Irrigation practice	

7.3 If you did not change your farming practices in response to drought or too much rain, why?

Key for 7.3 (why did you not change your farming practices?)

1. Lack of money
2. Lack of access to credit
3. Lack of access to land
4. Lack of inputs
5. Shortage of labor
6. Lack of information on climate change and appropriate adaptations
7. Other

8 Farmer's perception to long-term and short-term change

8.1 Have you noticed any long-term changes in the average temperature over the last 20 years?

______________________ *(If too difficult: Has the number of hot days stayed the same, increased or declined over the last 20 years?)* Key 1. Increased, 2. Decreased, 3. Stayed the same, 4. Don't know

8.2 Have you noticed any long term changes in the average rainfall over the last 20 years?

________________________ *(If too difficult: Has the number of rainfall days stayed the same, increased, or declined, over the last 20 years?)* Key: 1. Increased, 2. Decreased, 3. Stayed the same, 4. Don't know

8.3 Have you noticed any long term changes in rainfall variability over the last 20 years?

________________________*(If too difficult: Have the rains changed over the last 20 years?)*

Key 1=yes 2=no 0= don't know

8.3.1 If yes, what changes have you noticed? (Check all that apply)

Rains have become more erratic [ ]

Rains come earlier [ ]

Rains come later [ ]

Rains are heavier [ ]

Longer periods of drought [ ]

More floods [ ]

Other, specify________________________

8.4 Have you noticed any other changes in climate over the last 20 years, __________

(1=yes, 2=no) **if yes, please specify** ______________________________

8.5 What adjustments in your farming have you made to these long-term shifts temperature, rainfall, and variability?

Adjustments related to crops, livestock, both (key)	Investment cost	Life	Specify change
8.5.1.a.			8.5.1.b.
8.5.2.a.			8.5.2.b.
8.5.3.a.			8.5.3.b.
8.5.4.a.			8.5.4.b.
8.5.5.a.			8.5.5.b.
8.5.6.a.			8.5.6.b.
8.5.7.a.			8.5.7.b.

Appendix 2 *Boro* growing season Fixed-effect model

Table 2a STATA output of Boro growing season Fixed-effect model

```
  ___  ____  ____  ____  ____ (R)
 /__    /   ____/   /   ____/
___/   /   /___/   /   /___/   13.0   Copyright 1985-2013 StataCorp LP
  Statistics/Data Analysis            StataCorp
                                      4905 Lakeway Drive
                                      College Station, Texas 77845 USA
                                      800-STATA-PC        http://www.stata.com
                                      979-696-4600        stata@stata.com
                                      979-696-4601 (fax)

Single-user Stata perpetual license:
       Serial number:  301306235024
         Licensed to:  Fakir Azmal Huda
                       Humboldt University of Berlin

Notes:
      1.  New update available; type -update all-

. import excel "D:\Documents\Ph.D research\Ph. D Data\Data\BoroPool.xlsx", sheet("Sheet1") firstrow

. tsset  FarmersId Year
       panel variable:  FarmersId (strongly balanced)
        time variable:  Year, 2006 to 2013
                delta:  1 unit

. generate LnRTLan=ln( ReturnstoLand)
```

```
Fixed-effects (within) regression               Number of obs      =      2400
Group variable: FarmersId                       Number of groups   =       300

R-sq:  within  = 0.4549                         Obs per group: min =         8
       between = 0.0517                                        avg =       8.0
       overall = 0.0968                                        max =         8

                                                F(8,2092)          =    218.22
corr(u_i, Xb)  = -0.8219                        Prob > F           =    0.0000
```

LnRTLan	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
TempBoro	-.0412315	.0258097	-1.60	0.110	-.0918469	.0093839
prespBoro	.0030157	.001288	2.34	0.019	.0004899	.0055415
Age	-.0791496	.0089405	-8.85	0.000	-.0966829	-.0616163
VarD	.1569749	.0485733	3.23	0.001	.0617178	.252232
IrriD	.3126119	.0302355	10.34	0.000	.2533171	.3719067
Adtdam	.1758172	.0156068	11.27	0.000	.1452106	.2064237
PdnCost	-.0000874	3.91e-06	-22.34	0.000	-.0000951	-.0000797
X	.0024102	.0010099	2.39	0.017	.0004296	.0043907
_cons	15.65833	.8631051	18.14	0.000	13.9657	17.35097
sigma_u	.94652523					
sigma_e	.3875927					
rho	.85639745	(fraction of variance due to u_i)				

```
F test that all u_i=0:     F(299, 2092) =     7.07            Prob > F = 0.0000
```

Table 2b Box-Cox test for functional relationship assessment of Boro season model (log-linear model/semi-log model)

```
. boxcox  LnRTLan  TempBoro   prespBoro   Age  VarD  IrriD  Adtdam  PdnCost X, model(lhsonly)
Fitting comparison model

Iteration 0:   log likelihood = -2488.6846
Iteration 1:   log likelihood =  -2168.859
Iteration 2:   log likelihood =  -2164.056
Iteration 3:   log likelihood = -2164.0308
Iteration 4:   log likelihood = -2164.0308

Fitting full model

Iteration 0:   log likelihood = -1803.9906
Iteration 1:   log likelihood = -1356.1989
Iteration 2:   log likelihood = -1351.9435
Iteration 3:   log likelihood = -1351.9218
Iteration 4:   log likelihood = -1351.9218

                                                 Number of obs   =       2400
                                                 LR chi2(8)      =    1624.22
Log likelihood = -1351.9218                      Prob > chi2     =      0.000

------------------------------------------------------------------------------
     LnRTLan |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
      /theta |   6.153171   .2220541    27.71   0.000     5.717953    6.588389
------------------------------------------------------------------------------

Estimates of scale-variant parameters
----------------------------
             |      Coef.
-------------+--------------
Notrans      |
    TempBoro |  -31520.69
   prespBoro |   954.5242
         Age |  -146.2076
        VarD |      12361
       IrriD |   48844.38
      Adtdam |   19551.41
     PdnCost |  -8.20814
           X |   322.1415
       _cons |    1318006
-------------+--------------
      /sigma |   51933.75
----------------------------

---------------------------------------------------------
   Test         Restricted     LR statistic    P-value
   H0:        log likelihood       chi2      Prob > chi2
---------------------------------------------------------
theta = -1     -2696.6335        2689.42         0.000
theta =  0     -2129.8779        1555.91         0.000
theta =  1     -1803.9906         904.14         0.000
---------------------------------------------------------
```

Table 2c Hausman test for comparing Fixed-effect and Random-effect models of Boro season

.estimate store eq_fe, .estimate store eq_re; hausman eq_re eq_fe

```
. hausman eq_fe

Note: the rank of the differenced variance matrix (7) does not equal the number of coefficients being tested (8); be sure this is what you expect, or there
        may be problems computing the test.  Examine the output of your estimators for anything unexpected and possibly consider scaling your variables so
        that the coefficients are on a similar scale.

                 ---- Coefficients ----
             |      (b)          (B)            (b-B)     sqrt(diag(V_b-V_B))
             |     eq_fe        eq_re        Difference          S.E.
-------------+----------------------------------------------------------------
    TempBoro |   -.0412315    -.1315306        .0902991        .0050088
   prespBoro |    .0030157     .0071632       -.0041475        .0004566
         Age |   -.0791496    -.0048743       -.0742754        .0087813
        VarD |    .1569749     .1615304       -.0045554        .0323704
       IrriD |    .3126119     .3463187       -.0337068        .0069538
      Adtdam |    .1758172     .1391691        .0366481        .0068012
     PdnCost |   -.0000874    -.0000889        1.47e-06        2.13e-06
           X |    .0024102     .0032335       -.0008234        .0008183
------------------------------------------------------------------------------
                           b = consistent under Ho and Ha; obtained from xtreg
            B = inconsistent under Ha, efficient under Ho; obtained from xtreg

    Test:  Ho:  difference in coefficients not systematic

                  chi2(7) = (b-B)'[(V_b-V_B)^(-1)](b-B)
                          =      403.92
                Prob>chi2 =      0.0000
                (V_b-V_B is not positive definite)
```

Appendix 3 Amon growing season Fixed-effect model

Table 3a STATA output of Amon growing season Fixed-effect model

```
  ___  ____  ____  ____  ____ (R)
 /__    /   ____/   /   ____/
___/   /   /___/   /   /___/   13.0   Copyright 1985-2013 StataCorp LP
  Statistics/Data Analysis            StataCorp
                                      4905 Lakeway Drive
                                      College Station, Texas 77845 USA
                                      800-STATA-PC        http://www.stata.com
                                      979-696-4600        stata@stata.com
                                      979-696-4601 (fax)

Single-user Stata perpetual license:
       Serial number:  301306235024
         Licensed to:  Fakir Azmal Huda
                       Humboldt University of Berlin

Notes:
      1.  New update available; type -update all-

. import excel "D:\Documents\Ph.D research\Ph. D Data\Data\Amon pool.xlsx", sheet("Sheet1") firstrow

. tsset  FarmersId Year
       panel variable:  FarmersId (strongly balanced)
        time variable:  Year, 2006 to 2013
                delta:  1 unit

. generate  LnATLan= ln( ReturstolandAmon)
(1 missing value generated)

. tsset FarmersId Year
       panel variable:  FarmersId (strongly balanced)
        time variable:  Year, 2006 to 2013
                delta:  1 unit
```

```
. xtreg  LnATLan TempAmon PrespAmon T  PC Age VarAmon  AdtdAmon, fe

Fixed-effects (within) regression               Number of obs      =      2399
Group variable: FarmersId                       Number of groups   =       300

R-sq:  within  = 0.5747                         Obs per group: min =         7
       between = 0.0136                                        avg =       8.0
       overall = 0.0011                                        max =         8

                                                F(7,2092)          =    403.83
corr(u_i, Xb)  = -0.8096                        Prob > F           =    0.0000

------------------------------------------------------------------------------
     LnATLan |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    TempAmon |  -.1758474   .0259142    -6.79   0.000    -.2266678    -.125027
   PrespAmon |   .0056316   .0003383    16.65   0.000     .0049682    .0062951
           T |   .0000865   .0001955     0.44   0.658    -.0002969    .0004699
      PCAmon |  -.0000936   4.27e-06   -21.91   0.000     -.000102   -.0000852
         Age |  -.0815643   .0066738   -12.22   0.000    -.0946522   -.0684763
     VarAmon |   .0391832   .0251386     1.56   0.119     -.010116    .0884824
    AdtdAmon |   .1941283   .0140767    13.79   0.000     .1665225    .2217341
       _cons |   18.28995   .7859213    23.27   0.000     16.74868    19.83121
-------------+----------------------------------------------------------------
     sigma_u |  1.2497366
     sigma_e |  .29735845
         rho |  .94641944   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(299, 2092) =    24.10           Prob > F = 0.0000
```

Table 3b Box Cox test for functional relationship assessment of Amon season model (log-linear model/semi-log model)

```
. boxcox LnATLan TempAmon PrespAmon T  PC Age VarAmon  AdtdAmon , model(lhsonly)
Fitting comparison model

Iteration 0:   log likelihood =  -2819.828
Iteration 1:   log likelihood = -2738.0033
Iteration 2:   log likelihood = -2737.5419
Iteration 3:   log likelihood = -2737.5418

Fitting full model

Iteration 0:   log likelihood = -2119.3393
Iteration 1:   log likelihood = -2007.3336
Iteration 2:   log likelihood = -2006.8116
Iteration 3:   log likelihood = -2006.8114

                                                  Number of obs   =       2399
                                                  LR chi2(7)      =    1461.46
Log likelihood = -2006.8114                       Prob > chi2     =      0.000

------------------------------------------------------------------------------
     LnATLan |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
      /theta |   3.291271    .165928    19.84   0.000     2.966059    3.616484
------------------------------------------------------------------------------
```


```
. boxcox LnATLan TempAmon PrespAmon T  PC Age VarAmon  AdtdAmon , model(lhsonly)
Fitting comparison model

Iteration 0:   log likelihood =  -2819.828
Iteration 1:   log likelihood = -2738.0033
Iteration 2:   log likelihood = -2737.5419
Iteration 3:   log likelihood = -2737.5418

Fitting full model

Iteration 0:   log likelihood = -2119.3393
Iteration 1:   log likelihood = -2007.3336
Iteration 2:   log likelihood = -2006.8116
Iteration 3:   log likelihood = -2006.8114

                                                  Number of obs   =       2399
                                                  LR chi2(7)      =    1461.46
Log likelihood = -2006.8114                       Prob > chi2     =      0.000

------------------------------------------------------------------------------
     LnATLan |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
      /theta |   3.291271    .165928    19.84   0.000     2.966059    3.616484
------------------------------------------------------------------------------
```


```
Estimates of scale-variant parameters
----------------------------
             |      Coef.
-------------+--------------
Notrans      |
    TempAmon |   -204.236
   PrespAmon |   .5986664
           T |   .2874569
      PCAmon |   .0026975
         Age |  -.3453711
     VarAmon |  -20.16544
    AdtdAmon |   35.73483
       _cons |    6600.79
-------------+--------------
      /sigma |   90.71122
----------------------------

---------------------------------------------------------
   Test         Restricted      LR statistic      P-value
    H0:       log likelihood        chi2       Prob > chi2
---------------------------------------------------------
theta = -1      -2474.7167        935.81           0.000
theta =  0      -2258.9156        504.21           0.000
theta =  1      -2119.3393        225.06           0.000
---------------------------------------------------------
```

Table 3c Hausman test for comparing Fixed-effect and Random-effect models of Amon season

estimate store eq_fe., estimate store eq_re. , hausman eq_re eq_fe

```
. estimate store eq_fe

. xtreg  LnATLan TempAmon PrespAmon T  PC Age VarAmon  AdtdAmon, re

Random-effects GLS regression                   Number of obs      =      2399
Group variable: FarmersId                       Number of groups   =       300

R-sq:  within  = 0.4304                         Obs per group: min =         7
       between = 0.2242                                        avg =       8.0
       overall = 0.2746                                        max =         8

                                                Wald chi2(7)       =   1343.65
corr(u_i, X)   = 0 (assumed)                    Prob > chi2        =    0.0000

------------------------------------------------------------------------------
     LnATLan |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    TempAmon |  -.6850474    .030596   -22.39   0.000    -.7450145   -.6250803
   PrespAmon |   .0064333   .0004226    15.22   0.000      .005605    .0072616
           T |   .0005146   .0002403     2.14   0.032     .0000436    .0009857
      PCAmon |  -.0000563   4.10e-06   -13.71   0.000    -.0000643   -.0000482
         Age |  -.0019328   .0016961    -1.14   0.254    -.0052571    .0013914
     VarAmon |  -.1453775    .031098    -4.67   0.000    -.2063285   -.0844264
    AdtdAmon |   .1570364   .0155589    10.09   0.000     .1265416    .1875312
       _cons |   30.21957    .953932    31.68   0.000      28.3499    32.08924
-------------+----------------------------------------------------------------
     sigma_u |  .21798464
     sigma_e |  .29735845
         rho |  .34954782   (fraction of variance due to u_i)
------------------------------------------------------------------------------

. estimate store eq_re

. hausman eq_re eq_fe

                 ---- Coefficients ----
             |      (b)          (B)            (b-B)     sqrt(diag(V_b-V_B))
             |     eq_re        eq_fe        Difference          S.E.
-------------+----------------------------------------------------------------
    TempAmon |   -.6850474    -.1758474          -.5092        .0162655
   PrespAmon |    .0064333     .0056316        .0008017        .0002533
           T |    .0005146     .0000865        .0004281        .0001398
      PCAmon |   -.0000563    -.0000936        .0000373               .
         Age |   -.0019328    -.0815643        .0796315               .
     VarAmon |   -.1453775     .0391832       -.1845607        .0183069
    AdtdAmon |    .1570364     .1941283       -.0370919        .0066275
------------------------------------------------------------------------------
                           b = consistent under Ho and Ha; obtained from xtreg
            B = inconsistent under Ha, efficient under Ho; obtained from xtreg

    Test:  Ho:  difference in coefficients not systematic

                  chi2(7) = (b-B)'[(V_b-V_B)^(-1)](b-B)
                          =     2235.28
                Prob>chi2 =      0.0000
                (V_b-V_B is not positive definite)
```